

AN INVESTIGATION OF PATTERN VISION IN
THE HUMAN BY PSYCHOPHYSICS AND
EVOKED POTENTIALS

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ABSTRACT

A group of patterns formed from white and black dots in a two-dimensional array is designed to exhibit perceptual qualities of known importance to the spontaneous texture discrimination task. The texture qualities of interest, controlled by the specification of nearest neighbor dot correlations, are: granularity and vertical, horizontal, and diagonal directionality. The property of connectivity between dots in the array underlies the granularity and directionality qualities. The test pattern group formed the stimulus for a series of psychophysical and visually evoked scalp potential (VESP) experiments.

Spontaneous discrimination tests between members of the stimulus group taken in pairs were performed on three subjects. The object of discrimination tests was to obtain a measure of the relative perceptual dissimilarity among members of the group. The results of discrimination tests were analysed by a non-metric scaling technique (Kruskal, 1964a) which allowed identification of the perceptual processes underlying the discrimination task. It was found that a minimum of three independent processes are associated with the perception of granularity, vertical-horizontal directionality, and diagonal directionality, respectively. For two of the three subjects, the primary discriminant was the granularity quality while for the third subject the vertical-horizontal directionality percept was of primary importance. The diagonal directionality percept, while distinctly independent from the other perceptual processes, was the least important discriminant for all subjects.

Having characterized the perceptual aspects of the texture group

for each subject, VESP experiments were performed with several members of the group as stimuli to determine if any correlation could be found between the perception of the patterns and the scalp potentials they evoked. The patterns were shown in counterphase using an appearance/reversal paradigm. Recordings were made on each of the three subjects with multi-electrode arrays and the spatial distribution of the evoked potentials was analysed by a source localization model (Kavanagh, 1972).

The localization analysis displayed in a very lucid manner subtle differences in the distributions of scalp potentials evoked by counterphase stimulation with different members of the texture group. The variations quantitized by localization analysis were concerned with shifts in the potential distribution on the scalp which could hardly be discerned from visual inspection of the VESP waveforms on individual electrodes or even from equipotential contour maps of the scalp potentials. Source localization analysis thus allowed a measure of differences in the electrophysiological responses to different texture patterns.

The differences in VESP's for the different textures could be correlated with each subject's perceptual discrimination of the textures. The responses to textures of constant directionality but different granularity were localized in separate regions of our model, while responses for constant granularity but different directionality textures were located in similar regions but displayed different motion behavior.

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I. INTRODUCTION

Continually fluctuating electrical potentials are present at all times and in appreciable size on the scalp of normal living humans. "Brain waves" have historically received the attention of clinicians, researchers and charlatans alike. One's first impression upon studying an oscilloscope display or chart recording of scalp potentials is that somehow here is an access to the inner workings of the mind itself.

The problem of how the physical activity of the brain gives rise to the perceptual experiences of the mind was perhaps most well-posed by Descartes' classical statement, 'cogito ergo sum,' although it certainly predates Descartes. The role of scalp potentials in solving the mind-brain riddle has not been as significant as was perhaps first imagined; nevertheless they remain the one non-destructive physical measurement currently available to directly approach this problem.

The study of mental functions via scalp electrical potentials has passed through several stages. A major step was the discovery of signals in the electroencephalogram that correlated with the presentation of some sensory stimuli. Visual stimuli in particular, were found to "evoke" a characteristic potential when presented in an alternating fashion. A diffuse light flashed on and off for example causes a fluctuation in the scalp potential which, while to a large extent hidden by the other ongoing activity, can be recovered by averaging the EEG over many repetitions of the stimulus. The auditory and somatosensory modalities likewise, can be utilized to obtain characteristic signals from the EEG. In general, these averaged

evoked potentials are reminiscent of a system impulse response function where the impulse is the sudden alternation of some parameter in the stimulus.

The remarkable fact about the evoked scalp potential is its repeatability for a given subject in a particular experiment not only on sequential runs in the same session but over different sessions run on different days. A great body of evidence has accumulated over the years concerning the nature of these stable, characteristic responses and their relationship to various parameters of the stimulus and the subject. The visually evoked scalp potential (VESP) for example has been correlated with age, acuity, attentiveness, abnormalities and malfunctions of the subject and his visual system (Regan, 1972). Likewise, the response is known to depend on the intensity, size, color, duration, and structure of the flashed field. Unfortunately, no clear picture has emerged elucidating the precise mechanisms underlying the response and its various dependencies.

Neurophysiologists have endeavored to describe scalp EP's in terms of events recorded from individual neurons assuming that the EP's arise from the concerted activity of huge populations of cells. Unfortunately, the classical models of individual cells do not lend themselves well to consolidation into neural networks. Rall (1969) is one of the pioneers of neural network modeling. His efforts center on networks in which the individual cell models are minimally compromised. For this reason, the number of cells and the amount of arborization in the dendritic trees is severely restricted by computation time and space considerations even on the largest computing machines in use

today.

Other workers have been able to synthesize large networks of quite simplified unit models which can be solved readily and which do simulate the measured behavior of actual cells tolerably well provided appropriate assumptions are made. However, the gap between the single cell experimentalists and theoreticians and those attempting to handle large groups of neurons is formidable indeed. The fundamental issue is that of identification and control of the participating independent variables. When a squid axon is isolated and voltage clamped, only a certain few factors are able to contribute to its excitatory activity. Their behavior can be carefully measured with their operating environment held constant and well defined. Hence, the equations and models derived from such experiments are well founded. Hodgkin (1951), for example, described neuronal activity on the basis of ionic concentrations. Similar efforts to describe the behavior of integrated neuronal structures have not succeeded due to the complexity of the situation when constraints are removed. Eccles (1967) has done extensive studies of large neuronal structures through anatomical and electro-physiological description of their constituent neurons and the interconnections of those neurons. Eccles' approach follows the Herculean efforts of Ramon Y Cajal (1952) whose line drawings of neural networks are unsurpassed even by present electron microscopy techniques. Eccles' work has served to guide theoreticians such as Marr (1975) to construct quite feasible descriptions of the processing which large groups of neurons may be capable of performing. Such interaction of experimental data and testable theory should provide a most

expeditious route to the understanding of neuronal processes. Nevertheless, the path is littered with inconsistencies and anomalies which in some cases are simply beyond the scope of the basic approach taken by these investigators. As Rall is limited by computing capacity, so too are Eccles and Marr impeded by the overwhelming numbers of neurons and their wide variety of communication modes.

The activity of cells in mass can only be understood in the context of a precise characterization of single cell behavior. For this reason, the work of single cell experimentalists and theoreticians is invaluable; however, questions of a more global nature cannot be answered with their techniques alone. Likewise, models which duplicate behavior of large neural nets require some more encompassing approach for their experimental verification. The study of intelligent perceptual processes requires an understanding of the consolidation of groups of large neuronal structures into a coherent entity. Now it is unavoidable to link the efforts to describe scalp potentials in terms of individual neuronal events with the problem of disassociating a forest from its trees. Here once more the entity, if not greater than, is at least different from the linear summation of its parts.

If it is then difficult to work up from small neural nets to measured scalp potentials, is the path down from measured cognizant behavior to scalp electrical events any more favorable? Does the apparent correlation of evoked potentials to perceptual events provide new insight concerning the generation of those events? How does one interpret the fact that the amplitude of a signal averaged over 50-100 alternations of a chequerboard pattern will reach a higher value for

cheques on the order of 10 to 20 minutes of arc than for larger or smaller cheques; or the fact that the psychophysical threshold for brightness detectability can be extrapolated from measured scalp potentials? In general, if stimuli are found such that the variance in their perception correlates with the variance in the scalp potentials they evoke, there can be a variety of interpretations.

There is the advantage, albeit a somewhat mixed blessing, that the human subject can communicate his perceptual experience to the investigator. Hence, psychophysical testing of cooperative humans has less potential for the gross kind of blunder that workers with animal subjects must constantly guard against. The human subject is often more than happy to inform the investigator when his apparatus or procedure is not having the desired perceptual effect. Of course, the experimenter must be just as careful in designing his test as those using animal subjects simply because the human has the tendency to become bored and then try to outsmart the test setup in the interest of self-amusement. Nevertheless, having an alert, communicative human for psychophysical testing is an advantage which in many ways more than offsets the problems presented by the usual restriction of having to use some nondestructive procedure such as scalp electrodes to obtain electrophysiological data.

Hence, in deciding to study the human, the investigator thereby finds himself led along the path from single cell studies to evoked potentials to psychophysics. The last he can perform at his leisure, often with a minimum of apparatus. The second, while it presents more technical problems, is still within his grasp. Experimentation in the first area

however, is severely limited. Faced with these realities, it is clearly best to make a program of psychophysical tests and scalp potential measurements, if extensive testing of human subjects is envisioned.

The problems of characterizing the relationship of evoked potentials and perception are still just as imposing as those to do with relating single cell events to evoked potentials. Indeed, psychophysicists rely on the work of histologists and neurophysiologists to explain their results as much as do electroencephalographers. The evoked potential thus occupies a shadowy middle ground dividing two well illuminated areas; single cell neurophysiology and human psychophysics. The VESP has been utilized as an indication of activity in both areas and as a link to elucidate the relationship between the two areas.

The Psychophysical Problem

The investigation presented herein centers on a psychophysical measurement of visual perception in the human. The problem involved is that of determining the clues for discrimination among a particular group of patterns. Once the fundamental clues were identified, their relative weights and interdependencies were studied. The patterns were designed to contain appreciable amounts of a property known to be significant in pattern recognition problems; connectivity. A simple forced-choice discrimination task was constructed in order to obtain a measure of the dissimilarity among all members of the group. The resulting matrix of perceptual dissimilarities was treated by a non-metric, multi-dimensional scaling analysis.

Scaling is a recently developed technique for handling non-metric, perceptual data and recovering a metric representation for it

(Shepard, 1962). It is an off-shoot of classical factor and variance analysis techniques specially designed for the problem in which factors are not identified and dimensionality is unknown. Dimensionality is, in fact, the mechanism utilized to indicate the active variables in the data and their interrelations. The term "scaling" itself refers to the construction of a metric structure in a hyper-space of some arbitrary dimensionality. Each point of the structure represents a member of the group of objects under study. The metric interpoint distances in some way relate to the non-metric dissimilarity measures. The structure is constructed according to some optimization rule so that the interpoint distances "fit" or represent the perceptual data as well as possible for the given dimensionality space. Some quantitative measure is made of the "goodness of fit" for structures in different order spaces. The hypothesis for doing this is that for spaces of order equal to or greater than the number of active variables in the data, the structures should fit the data with approximately the same "goodness". When the order of the space is reduced below the number of significant variables, an abrupt degradation in the "goodness of fit" is expected. This is because an important component of the data has not been accounted for. Hence, a plot of dimensionality against "goodness" should provide an indication of the number of factors operative in the perceptual experiment.

The end product of a scaling analysis applied to the perception of some group of objects is therefore the optimized structure in the space of minimum dimensionality and acceptable "goodness of fit". This structure is a metric representation of the perceived differences

among objects in the group. The rank ordering of interpoint distances naturally provides the ranking of perceptual separation starting from the most different pair of objects to the most alike. Careful study of the structure can reveal more about the perceptual processes involved than is apparent from the rank order. Analysis of variance techniques can be used to define either the axes of the structure along which interpoint variance is a maximum or the axes of zero correlation. A study of the objects lying along the maximum variance or principal components axes can yield clues concerning the perceptual factors responsible for the observed variance. Objects which are found to lie on axes which have zero correlation may be representative of percepts which are independent in some sense. Objects which lie at different points on the same axis may share the same percept but differ in the degree to which they represent that percept.

A complete characterization of the objects in the group being studied according to their physically measurable properties is essential to not only the interpretation of the recovered structure but also the validity of the scaling solution as well. Each object point must be precisely defined according to all its physical properties, both those it has in common with the rest of the group and those unique to it. The actual objects used for experimentation must fit their object point descriptions exactly. The human is too clever an operator for anything but the most precisely defined test conditions. If the psychophysical test contains unknown, uncontrolled variables, the subject may provide answers to quite different questions from those the investigator has asked. No powerful analysis technique can ever

compensate for a poorly designed or executed experiment.

The property of connectivity was central to all the discriminations performed in the psychophysical tests reported herein. Other workers have attempted a precise, mathematical definition of connectivity (Minsky, 1969). With respect to patterns constructed of dot arrays, our approach has been to think of connectivity as a more qualitative term for the cross correlation between dots in the array. In turn, when dots are restricted to being only black or white, correlation is a function of the probability of a given dot being the same as or different from its nearest neighbor, next nearest neighbor, or whatever. For simplicity, the dots in the arrays used throughout these tests were restricted to either black or white, and the probabilities were reasonably high so that well defined patterns, all of equal brightness, would emerge. The arrays thus constructed stimulated quite distinct percepts or combinations of percepts.

Connectivity, as we define it, is closely related to directionality. If connectedness exists in an array by virtue of proximate dots having the same brightness, distinct directions will be defined. These directions are dependent on the choice of nearest neighbor relations. For the arrays used herein, the polarity of each dot was a function of the combined polarities of the nearest vertical, horizontal, and diagonal dots. This choice resulted in patterns which generated distinct percepts of verticality, horizontality, and diagonality.

Connectedness in a dot array also underlies the perceived sensation of granularity in the field produced by the dots. A high degree of nearest neighbor correlation results in the formation of clumps of

dots having the same brightness level. Likewise, negative correlation (i. e. nearest dots are likely to have opposite polarities) gives a smooth field with fine graininess. Other authors (Richards, 1974) have defined granularity in terms of the spatial frequency spectrum of the displayed brightness distribution. A predominance of low frequencies results in clumpiness while a spectrum weighted toward high spatial frequencies gives a smoothed-out or salt and pepper effect.

Hence by starting with connectivity, we produced a group of textures that generated various combinations of directionality and granularity percepts. The goal of our psychophysical experiments with these stimuli was to determine their relative strengths and interdependencies in order to characterize the mechanisms underlying their discriminations. The analysis of the minimum dimensionality configurations obtained by scaling the experimental results provided the desired mathematical description of how the test stimuli group was processed. The configurations themselves formed a primitive model which could serve as the basis for more elaborate models or generate hypothesis for electrophysiological testing.

The Electrophysiological Problem

Having obtained perceptual results on the texture discrimination problem, the question logically arises as to whether or not these results have electrophysiological significance. Being of the mind that a physical measurement is often more convincing than the most rigorous theory, the author chose to search for electrophysiological correlates rather than fit the perceptual test results to some model.

Now a variety of patterns have been used in VESP studies on the

human. Historically, the progression of visual stimuli has gone from large uniform fields to small discrete points, to slits and line gratings and to chequerboard fields. For a given subject, each of the aforementioned stimuli have been found to evoke somewhat different characteristic potentials in the same experimental conditions. Moreover, the observed responses are often dependent on the method of display presentation. Workers have typically reported changes in latency, amplitude and waveshape of the VESP recorded for each of the aforementioned stimuli in different presentation conditions. Hence, an immediate question arose concerning the display method for the group of stimuli being studied.

The criterion for choosing the optimum presentation mode ultimately turned on the isolation of pattern-specific components in the evoked potential. The results of similar experiments by other workers provided useful guidelines. The technique of flashing a pattern, for example, was discarded since the flash evoked potential is known to be contaminated by light scattered randomly on the retina by the various optical components of the eye. To alleviate the scattering problem and allow a precise definition of the activated retinal area the technique of stimulus reversal has been developed and extensively employed by Riggs (1966), Armington (1971), Spekreijse (1973), and others. In general, however, the patterns used in reversal stimulation have been either bar gratings of various spatial frequencies and orientations or uniform chequerboard arrays. Hence, an investigation of the variation in the VESP due to variations in the statistics among arrays of identical brightness would examine a new aspect. The

determination of whether or not such a dependency exists would add to the body of knowledge concerning the VESP.

The whole problem of interpretation of such empirically determined relationships nevertheless remains to be dealt with. Here again, the investigator who has only scalp potentials at his disposal is forced to fall back upon the work of the neurophysiologist for detailed interpretation of his data. True, a physical foundation has been established for some perceptual phenomena, however, one is left with the distinct feeling that here is not the entire answer. In general, at this point the classical studies of the functioning of visual cortex are incorporated into a hypothesis consistent with both the psychophysical and the evoked potential results. Indeed, since so much has been learned from the work of single cell neurophysiologists concerning the structure and functioning of the visual system, it is extremely important to evaluate any new piece of vision research with regard to that body of knowledge. Nevertheless, there is a further analysis which can be performed (when facilities are available) in the effort to extract from the evoked potential data itself greater insight on the visual processes involved. This further approach receives a good deal of attention in the present work; it is source localization analysis and the laboratories of Fender at Caltech are uniquely equipped for its implementation.

Source Localization Analysis

The hypothesis of the existence of discrete, localizeable sources active during the time course of an evoked cortical potential is one of long standing controversy. It is attractive and plausible because spatio-temporal maps of an EP are strikingly similar to the electric

field distributions generated by postulated discrete sources enclosed within head-shaped geometries containing hypothetical media with anisotropic properties. Therein, however, lies the first problem of implementing the source theory: the great difficulty of accurately modeling the behavior of living tissue in a real head. Furthermore, there is some amount of ambiguity concerning the postulated existence of discrete generators for the observed scalp activity. Both these questions require careful consideration before a source analysis of evoked potentials is adopted. Experimental results must be evaluated with regard to the existing anatomical and functional knowledge of the visual system to support the interpretation of localization solutions. In this work, the activity of localized sources is interpreted in a relative sense. Movements of sources for different times during a response and for different stimulus conditions are taken as indicative of changes in the neural activity underlying the evoked response. The study of these relative source changes and their relation to stimulus parameters in the context of known visual cortex functional architecture is the most tenable approach to the utilization of a source solution for EP activity. The capability of a source model to reveal variations in the EP which are not discerned by the usual techniques of comparing wave shapes or even equipotential maps is the best argument for its adoption.

Spatio-temporal mapping of scalp potentials in itself is an attractive approach to the problem of interpreting evoked potential data. Instead of having a group of electrode tracings to consider, the entire field over the surface of the head is presented. This gives the

investigator a greater insight to the manner in which the response at each electrode site correlates into the entire activity pattern. The spatio-temporal map in itself can be considered as a two-dimensional localization of activity over the electrode array. Both the location of active sites and their cross-correlation in time and space are displayed in an easily understandable fashion.

Using The Source Model

The construction of a contour map of equipotential lines is the first step in attempting to treat the VESP as a unified vector phenomenon and not as a set of independent scalar measurements. Mapping assumes an implicit correlation of points that share the same potential with respect to some reference at a given instant during the time history of the response. The correlation may arise via one of two possible mechanisms; 1) equipotential points are driven from a discrete source within a passive conducting media, or 2) equipotential points are closely interacting sites in an active media. Either possibility could yield identical scalp potentials and hence no distinction can be made on the basis of scalp measurements. In case 1 a discrete source consisting of a block of cells perhaps 1mm on a side drives the voltages on the scalp via passive conduction. Signals at a given electrode site originate at the remote source. In case 2, signals at each electrode originate from neuronal activity close to the electrode site. The signals at each electrode site are driven from a remote source perhaps originating in association areas of the thalamus and propagated via the various thalamo-cortical tracts thus explaining their high degree of coherence. Although the source model explicitly

hypothesizes case 1, passive conduction, its results are not useless should case 2, neuronal activity, be the actual situation. The cortical activity is characterized very precisely in 3 dimensions by the source model regardless of whether that activity originates via the case 1 or case 2 hypothesis.

If passive conduction is the true situation, then localizations defined by the source solution depend only on how well the geometrical and electrical parameters of the model head can be made to match the subject. If data from depth electrodes is available, the match can be done quite accurately. When responses of longer latencies are studied so that feedback activity through the midbrain is possible, the solution obtained by a passive conduction model is still representative of the locus of cortical activity; it simply does not tell the entire story of the origin of that activity.

In using the source model to study evoked potentials, the emphasis herein has been on the capability of the model to distinguish among potential fields on the scalp driven from slightly different stimuli. Usually a homogeneous sphere was used to represent the subject's head. Hence, no great positional accuracy is claimed for any of the localizations thus obtained. Nevertheless, the use of a source model is still advantageous in an interpretive sense. When a very good match between model and data is obtained, there can be no doubt that the activity is centered at a principal site in the cortex, regardless of whether or not feedback loops from other areas of the brain are involved. Thus the interpretation that locational changes in the focus of cortex activity are responsible for the variations in scalp potential

distribution has credibility. The source model can detect locational changes with a good deal of sensitivity, hence its utility in analyzing scalp potentials is clear.

Summary

The primary concern of this work is in characterizing the mechanisms of pattern vision in the human. The investigation centers on the perceptual and electrophysiological responses of subjects to a group of simple patterns carefully defined. While the experiments themselves were generally of a conventional nature, the utilization of rather novel techniques was explored in interpreting the experimental results. Thus to some extent this work can be described as the application of new computerized analysis methods to the classical problems of pattern vision.

Psychophysics and evoked potentials being the basic avenues of access to visual processing in a normal living brain, the new techniques presented herein are explored in the interest of extracting as much information as possible via those routes. The shortcomings of these tools are examined so that a fair evaluation of their utility can be made.

The basic question in these experiments is what are the clues used to discriminate among the stimuli patterns and are these clues distinguishable in the study of evoked potential data. The question follows a classic line which has been used successfully in many studies of vision and other brain functions. In this case our stimuli contained fundamental properties of known importance to pattern vision. The results of studying these experiments via the new techniques of scaling and source analysis are quite straightforward. The techniques have

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proved useful in providing insight into the fundamental question of this investigation.

II. VISUAL STIMULI

Introduction

In applying the classical input/output method of analysis, the first consideration is to the kind of stimulus one uses to interrogate the entity in question. When planning the study of an alert, cognizant human, the question of stimulus is indeed paramount. In the study of electrical engineering the distinction is made between linear and nonlinear systems. The tenets of systems theory have been adopted by many investigators and found to be quite applicable to the study of neuronal function where nonlinear techniques have proved fruitful. With the exception of threshold studies where small signal approximations can be made, the extension of stimulus-response descriptions to perceptual and emotional behavior of an independently operating organism has met with mixed results. The problems encountered in attempts to characterize a human response are due in large measure to the multivariate nature of the human operator. In studying human vision, one must always be aware that it is a complete functioning human he has under test and not merely a visual system.

Human visual response has been investigated through the use of numerous stimuli that in general have been characterized by linear harmonic analysis. Such devices as lines, points, and gratings have been used to analyze visual functions through linear systems theory in both psychophysical and neurophysiological studies. Many human experiments are extrapolations of work involving direct recording from visual pathways in animals. Thus in choosing a visual stimulus suitable to a particular study, the investigator is able to draw on a

wealth of data from both neurophysiological and psychophysical experiments on both human and animal subjects.

In this investigation, stimuli were chosen in the first instance with regard to their effectiveness in a human electrophysiological experiment, i. e.; their ability to generate cortical responses measurable on the scalp and directly interpretable in terms of stimulus parameters. The results concerning processing of various stimulus parameters that have been obtained from recordings in visual cortex of cat and monkey were consulted to determine their implications on human experiments. Finally, psychophysical studies on the perceptual aspects of visual stimuli were considered in order to characterize the percepts associated with the stimuli.

Evoked Potential Techniques

The presentation of a visual stimulus to the eye elicits a fluctuation in the electrical activity on the scalp of the observer. Unfortunately the disturbance is often so small in relation to the ever present ongoing scalp electrical activity that it cannot be detected. In order to detect scalp potentials that are related to a visual stimulus, the stimulus is presented repetitiously, and the recorded scalp activity averaged over a number of presentations. If activity occurs in a repeatable fashion for each presentation, the averaging technique will cause that activity to accumulate in direct proportions to the number of repetitions, N . If the noise in the measurement is purely random, it will be accumulated in proportion to $\sqrt{N}$.

The technique of averaging for the purpose of improving signal to noise ratio is optimum in the case of a signal present in normally

distributed noise. The physiological activity measured via scalp electrodes however, does not have a normal distribution. Hence, the technique of averaging out spontaneous scalp activity as originated probably by Dawson (1947), has given way to the slightly different approach of calculating the median value of the activity on consecutive repetitions of a stimulus. The scalp activity is often contaminated by enormous potentials generated by the great muscles of the neck or by eye muscles. Also mechanical noise of sufficient amplitude to saturate the very sensitive preamplifiers can arise via such activity as a blink, a squint, wrinkling of the brow, etc. All the aforementioned disturbances usually do cause a momentary saturation of the amplifier which leads to nonlinearities and distorts the distribution of output signal. Hence, in our work, we have not averaged our sampled output signals but rather have taken the middle value or median value of the sample space as the best estimate of the true population mean. Furthermore, the data used in all our calculations is in fact the mean of a number (5-7) of replicates of the median values for each sample time under identical stimulus and recording conditions. By replicating our results we are able to estimate the standard deviation of the median values from the population means and obtain a figure of merit (signal to noise ratio) for our data.

Once it was determined that a measureable response could be elicited from the cortex via the scheme of repetitious presentation of a visual stimulus, the investigation of the precise relation of stimulus to response commenced in earnest. Early studies of responses to visual stimulation obtained from the human electroencephalogram,

(Brazier, 1958; Vanzulli et al. , 1960) encountered some difficulties in obtaining a stable stimulus/response relationship. Cobb and Dawson (1956) reported finding considerable variation in the evoked response to visual stimulation under constant stimulus conditions.

Tepas and Armington (1962), measured summed responses to repetitive visual stimuli and the relation of response amplitude and latency to stimulus luminance. A uniform circular beam subtending angles from $24'$ to 15° was presented to the subject in Maxwellian view at stimulation rates ranging from 1 to 20 flashes per sec. The experimenter was able to control the stimulus area, luminance and spectral composition. Recording was done from bipolar electrodes placed on the midline approximately 1 inch above and below theinion. In most cases the electroretinogram (ERG) was recorded as well.

The experiments were performed in three parts: first a series of sessions on successive days in which stimulus luminance, area, spectral composition, and repetition rate were held constant; next recordings were made for a white stimulus of 8° angular subtense at 1 rep/sec. with luminance varied over an 8 log unit range on successive trials during the same session; finally, both luminance and area of the stimulus were varied on successive trials in order to determine the combinations of area and luminance necessary for a constant evoked response. In the latter two parts of the experiments, ERG was recorded simultaneously with EEG in order to compare the relative parameters of these two responses.

Analysis of the averaged records from all experimental sessions by Tepas and Armington showed that while the occipital response did

show variability not traceable to any stimulus parameter, it also provided electrophysiological correlates previously unobtainable. In particular, the scalp potentials showed significant response to light levels which elicited no response in the ERG. In fact, the occipital response only disappeared when stimulus luminance approached the subject's absolute threshold. The latency of the VESP was quite linearly related to stimulus luminance. Latency decreased as brightness increased and reached its minimum for the brightest stimulus condition. The waveform of the EP contained a prominent biphasic complex which dominated most of the records and behaved quite unpredictably. Non-stimulus related factors such as motivation and attention may have been involved in the complexity of the waveshape; retinal and neural adaptation were also suggested. The results of area-luminance tests were particularly complicated for the occipital response. The problem of stray light scattered by the optical media within the subject's eye to random locations on the retina was considered a likely source for the uncorrelated behavior observed in the averaged scalp waveform.

The problem of stray light within the eye itself as well as in associated stimulus optics has been recognized by various investigators (Boynton and Riggs, 1951; Van Hof, 1964) as contributing to otherwise inexplicable variations in both ERG and EEG recordings since it was first pointed out by Fry and Bartley (1935). Independent studies by Boynton and Riggs (1951) and by Asher (1951) showed that flashes imaged on the blind spot evoked responses quite similar in form and even larger in amplitude than responses to the same stimulus imaged

on other parts of the retina. For the ERG, it has been hypothesized that light scattered or reflected to rods on the peripheral retina where gross sensitivity is quite high can elicit a greater response than light focused on the macular where cone density is greatest and gross sensitivity somewhat lower. It is further assumed that this problem exerts an influence on the activity in occipital cortex as well. A technique for minimizing the problem of stray light has been developed by Riggs, Johnson, and Schick (1966) and extensively implemented by Armington (1967), Spekreijse (1973), Jeffreys (1971), and others. This method of dealing with the stray light problem has come to be known as the technique of stimulus alternation or counter-phase stimulation.

A stimulus alternation display is simply a pattern of bright and dark areas whose polarity (i. e. bright or dark) can be modulated. The bright areas of the pattern are uniformly switched to dark while simultaneously the dark areas switch to bright. The "switching" described here can be an abrupt square wave or a smooth sinusoidal modulation and it has been done at various frequencies from 1/sec. to 60-70/sec. Early work by Johnson et al. (1966) employed a pattern of vertical bars of contiguous bright and dark regions. The bars were abruptly displaced at a low rate (1-2/sec.) so that bright areas were replaced by dark areas and vice versa. At the lower repetition rates, the alternating bars give a distinct motion percept and sometimes seem to march across the field of view as though on a rotating drum. The total light entering the eye at any instant during pattern alternation is held constant and therefore the scattered light is constant.

Armington (1968), used an alternating bar stimulus to investigate

the area-luminance relation for summed ERG and EEG records under the assumption that the stray light problem would be alleviated. He obtained good correspondence of ERG and EEG response vs. stimulus area curves. Moreover, the results support the contention of Johnson (1966) that the pattern alternation response is triggered mainly by cone receptors, i. e. is a photopic response dominated by cone-rich areas of the fovea. This also supports the hypothesis that the stray light response is mainly scotopic and originates from random points in the peripheral retina when a stimulus is imaged centrally. Hence, the counter-phase presentation technique allows a reasonable degree of confidence that an averaged response is stimulated by optical activity on the retina only where the stimulus is imaged. For an image fixated foveally this implies the VESP arises from those areas of striate and prestriate cortex that process information originating on the fovea.

Halliday and Michael (1970), Jeffreys (1971), and others have pursued the issue of the anatomical origin of the scalp potentials evoked by pattern reversal stimuli. The data presented by both Jeffreys and the Halliday and Michael papers show consistent and systematic changes with variations in the position of the stimulus in the visual field.

Electrodes placed in a row along the midline from vertex to inion show significant differences in averaged signal as a function of stimulation of upper vs. lower half fields and various octants within those half fields. Not only does the amplitude of the predominant peak in the VESP change when different portions of the visual fields are stimulated, but also a consistent polarity reversal of the largest peak is observed. These experiments were done with either alternating or

appearing/disappearing chequerboard displays subtending between 3° - 9° and foveally fixated. The apparent cheque size was in the range $15'$ - $30'$. In the case of pattern appearance/disappearance, a uniformly illuminated field of equal subtense and local brightness replaced the pattern. The appearance/disappearance stimulus used in the Jeffreys work gave an EP which contained a significant early latency peak at about 80 ms. Halliday and Michael, using a phase-reversing chequerboard, did not report any early peak before the prominent wave at 100 ms. While Jeffreys considered his early peak to arise from striate cortex lying within the calcarine fissure, both he and the Halliday and Michael group placed the major peak chiefly in extrastriate cortex on the external surfaces of the occipital lobes. The shifting of peak activity up and down the array of midline electrodes is consistent with the known retinotopic maps of the occipital lobes (CIBA, 1958). The two investigators offer contrasting hypotheses for the observed polarity reversal between responses to upper and to lower visual field stimuli; Jeffreys draws on the topography of extrastriate cortex to argue for a dipole representation of the activity in the two half fields while Halliday and Michael argue for two distinct sets of neurons possibly at different layers in extrastriate cortex.

The experimentation with constant illumination stimuli has therefore pointed to where activity is taking place in the cortex. The question of what kind of activity is responsible for the measured scalp potentials has thus far received only a small amount of attention. Spekrijse et al. (1971) used an appearing/disappearing chequerboard display to one eye and a constant chequerboard to the same retinal

position of the other eye to investigate the correlation of EP's to features of perception such as subjective interocular rivalry, and interocular and monocular suppression. The investigation clearly showed a link between the perception of contrast changes and the amplitude of the EP. Spekreijse's results also confirm the finding of Jeffreys and others that the distribution of the contrast evoked potentials is dependent on position of the stimulus within the field of view.

A very thorough investigation of the relation of various stimulus parameters to evoked potentials was performed by Campbell and Maffei (1970). These investigators used a grating stimulus with sinusoidal contrast reversal at the rate of 8 Hz. They measured response between an electrode on the inion and an electrode placed 1" temporally. The amplified scalp potentials were filtered through a quite narrow band pass with high and low cut-off frequencies at 8 and 25 Hz. respectively and attenuation of 40 db/decade out of band. The resultant VESP from the narrow band filters was a smooth sinusoid at approximately 16 Hz. The technique of filtering and the choice of an 8 Hz. repetition rate were adopted on the basis that a simple measurable response could be so obtained. Psychophysical measurements of the threshold contrast at which a grating could just be discerned were performed for spatial frequencies in the range of 3-18 c/deg. The phase-alternation evoked potential was measured as a function of contrast and it was found that the VESP amplitude was linearly related to the log of contrast. The slope of the amplitude vs. log contrast curve was constant for the spatial frequencies used. Moreover, the amplitude vs. log contrast regression lines were parallel for gratings oriented in the vertical,

the horizontal, and the diagonal. Both the psychophysical and the VESP contrast threshold were measurably higher for diagonal gratings than for vertical or horizontal.

Having obtained the repeatable linear relationship between log contrast and VESP, the investigators set out to define the stimulation parameters most critical to it. In particular, they were interested in factors which might lead to a change of slope in the amplitude/log contrast plot. As a first case, they tried and found the stimulus area to be rather ineffectual in altering the slope. Next they compared monocular and binocular stimulation; it too, did not affect the measured slope.

At this point a consideration of evidence for orientation and frequency selective channels obtained from single-cell recording led to the examination of the effect of stimulus orientation and size on the slope of the log contrast vs. VESP amplitude plot. By an optical construct, two identical images, one rotated with respect to the other, were presented to the two eyes. Phase alternation of the image in either eye viewed monocularly yielded log contrast/amplitude curves of identical slope regardless of the relative orientation of the image in one eye to the image in the other. When the stimulus was viewed binocularly, such that one eye saw a vertical phase-reversing grating, while the other eye saw a horizontal one, the slope of log contrast/amplitude doubled. The authors concluded that summation of activity in two separate orientation channels could account for their result. Likewise, stimulation with different spatial frequencies simultaneously yielded a significant change in the critical slope of log contrast vs. VESP amplitude. Here is one of the few examples in the literature (see

Moskowitz et al. (1974) for another) where the VESP has been used to show neurophysiological evidence of human visual processing similar to that obtained by microelectrode recording from visual cortex of cats and monkeys.

Thus, the technique of phase alternation is clearly capable of yielding straightforward results not only in regard to location of activity in human visual cortex, but also in regard to the nature of that activity. The choice of stimulus alternation frequency by the various experimenters mentioned has been governed by considerations of response amplitude, repeatability, and interpretability. While sinusoidal modulation in the 8-20 Hz. range as used by Campbell and Maffei gives strong, repeatable EP's, their interpretation is clouded by their close resemblance to the alpha wave complex. On the other hand, abrupt pattern appearance and reversal presented at intervals of 1 second or slower allows study of components with different latencies and is in more general usage. The key to determination of the stimulus pattern characteristics (contrast, orientation, etc.) and proper interpretation of the results lies in careful consideration of the information from psychophysical tests on the human and from depth electrode studies in animals.

Information from Animal Studies

It has been known for some time from the work of Hartline (1938, 1949), that the firing of retinal ganglion cells is influenced by light incident on restricted areas of the retina. The particular region of retina associated with a ganglion cell is known as the receptive field of that cell. Ganglion cells of cat were shown by Kuffler (1953), to

have concentric receptive fields composed of either an "on" center and "off" surround or vice versa. The "on" or excitatory areas and the "off" or inhibitory areas are known to be mutually antagonistic. It was found (Barlow, Fitz Hugh and Kuffler, 1957) that a spot subtending only the central field was more effective in eliciting spikes from the ganglion cell than a spot covering the whole field.

Working in cat, Hubel and Wiesel (1959) were able to describe similar receptive fields for cells of the striate cortex. Some of these fields were also divided into separate excitatory and inhibitory zones. However, the concentric pattern observed in retinal ganglion cells was not present in the receptive fields of striate cortex units. A commonly found arrangement was a central area with opposing flanks. Centrally excitatory and centrally inhibitory fields were found in approximately equal numbers. Fields with either long narrow central regions with extensive flanking areas or large central areas with concentrated slit-shaped flanks were a common configuration. Asymmetry of size and shape in the two flanking regions was often found. For asymmetric fields the same stimulus gave unequal responses in corresponding regions. For some units, the receptive field was comprised of only one excitatory region and one contiguous inhibitory region.

The response of two region receptive fields was critically attuned to the position of the stimulus light/dark boundary. Three-region fields were highly sensitive to the relative orientation of an elongated stimulus to the axis of symmetry of the field. Fields with optimal response axes oriented vertically, horizontally, and obliquely with respect to the animal's skull were found in equal number. Later work

by Mansfield (1974) in primates has however shown predominance of vertical and horizontal specific cells over oblique. Once the stimulus orientation for optimal response was defined for a given cell, the cell activity could usually be completely extinguished by placing the slit or edge orthogonal to its optimal position. The overall size of the receptive fields reported was 4° to 10° . Stimulation was performed with 1° spots of light and elongated slits typically $1^{\circ} \times 10^{\circ}$. Illumination in the photopic range could change several log units without affecting the size and shape of the receptive field.

In their early work, Hubel and Wiesel found receptive fields of cat striate cortex cells that were activated by ipsilateral, contra-lateral, and bilateral stimulation. Fields described with stationary stimuli and then interrogated with moving ones often responded in ways consistent with their stationary behavior. For example, in a field with a large inhibitory center and narrow asymmetric excitatory flanks, response favored movement in the direction of the stronger flank. Motion from one region to an opposite-type region within a receptive field gave a synergistic response that could greatly exceed the response to stationary stimuli in either region. In a binocular unit just as within a monocular field, the two (normally superimposed) receptive fields showed synergistic and antagonistic interactions between opposite-type regions. These findings suggested the receptive fields of striate cortex cells might be concerned with the determination of stimulus form, size, and orientation, and also with the perception of stimulus motion.

In a further report (Hubel and Wiesel, 1961), a second class of visual cortex cells was introduced. The behavior of these cells of

cat visual cortex was found to differ in certain critical aspects from the response behavior of the cells initially reported. Hubel and Wiesel classified the first group of cells "simple" and the second "complex" according to the following criteria. Cells were classified as "simple" if; 1) their receptive fields were subdivided into distinct excitatory and inhibitory regions, 2) there was summation within the separate regions, 3) antagonistic and synergistic behavior was exhibited between opposite-type regions, 4) responses to stationary or moving spots could be predicted from a map of the excitatory and inhibitory regions.

Somewhat less than 1/3 of the cat striate cortex cells reported by Hubel and Wiesel did not obey the aforementioned description and were hence classified "complex". Responses to an optimally oriented stimulus for complex cells were often mixtures of "on" and "off" firing. While field size was generally larger for a complex cell than for a simple* cell, increasing the stimulus size within the limits of the field size often had no effect on response. Despite having larger receptive fields than simple cells, complex cells often responded optimally to small stimuli properly oriented. Orientation of the stimulus remained critical for complex cells just as in simple cells. The optimal stimuli for complex cells in general were the same as for simple cells; slits, edges, and dark bars. However, small stationary spots of light were usually ineffective in eliciting any response from complex cells and yielded no consistent maps of the complex cell receptive field. Just as for simple cells, binocular stimulation was found to be effective in the majority of complex cells tested. Summation was observed when homologous regions of the two retina were

stimulated simultaneously. The relative influence of the two eyes varied for different cells from cases where both eyes were equally effective in eliciting a response to cases of strong monocular dominance. The general finding for both complex and simple cells is that the major portion of the cells studied are influenced by both eyes and on average the contralateral eye is dominant.

Thus, both simple and complex cells, while differing in many respects, may be classified under the general headings of retinal position, preferred axis orientation, receptive-field functional organization, and ocular-dominance. It is of particular interest to the present study to learn if cells grouped under one or more of the aforementioned headings are distributed throughout the visual cortex in some uniform arrangement. If many cells representing a particular region of retina are grouped closely together then optimal stimulation of that region should produce a high level of neuronal activity in a specific location of cortex. If this hypothesis can be extrapolated to human visual centers then it seems likely that such concentrated neuronal activity may be the source of the scalp potentials which form very coherent surface maps at certain times during the visual response. Moreover, the components of the visually evoked scalp potential may be explained in terms of receptive field theory. The following evidence on the functional cytoarchitecture of the cat's visual cortex from the Hubel and Wiesel work thus is a valuable guide for the present study on humans.

The data from multiple recordings made at numerous sites in cat post-lateral gyrus strongly indicate that both simple and complex cells are systematically arranged in a quite uniform columnar structure.

The columns run perpendicular to the six identifiable layers of cat visual cortex from the surface to the white matter beneath. On the surface, the columns are on the order of a half millimeter in width. Cells within a column are all optimally activated by the same angular orientation of an elongated slit stimulus. Adjacent columns contain cells which are specific for distinctly different orientations. Cells with common orientation preference are therefore not randomly distributed throughout the cat visual cortex but are well organized in distinct groupings.

The retinotopic specificity of cells in cat visual cortex has been well defined anatomically and physiologically; Minkowski (1913), Talbot and Marshall (1941). The region of cortex representing the $5-8^{\circ}$ central field angle is quite large in comparison to the region devoted to the rest of the visual field. Within the cortical representation of the area centralis only a slow variation in positional specificity is possible. Within a column of cells sharing a particular receptive field-axis orientation, the retinal position specificity was not found to change from cell to cell in any uniform manner. The complete fields of the cells were not perfectly superimposed but varied slightly in an apparently random fashion.

The ordering of cells according to eye dominance and receptive field arrangement was not clearly defined by the early Hubel and Wiesel work. Eye dominance was found to change within a given orientation-specific column and cells of quite different organization were found. There was some association of simple and complex cells with certain cortical layers. Both cells of similar organization and

eye dominance were often found in small groups within an orientation specific column.

The Hubel and Wiesel work has certain implications for our study on human vision. One inference is that uniform, symmetrical stimuli are not well matched to the receptive fields of any one group of visual cortex cells but rather excite many groups indiscriminately. The visual cortex (at least in cat) contains no cells whose receptive fields are of the symmetrical, concentric center-surround variety characteristic of retinal ganglion cells. A uniform chequerboard, for example, contains equal amounts of vertical and horizontal and the two diagonal orientations. The columnar structure of visual cortex described by Hubel and Wiesel is ordered according to either vertical, horizontal or oblique orientation selectivity: a given column (consisting of thousands of cortical cells) is responsive to only one such orientation. Moreover, for a cell of a given orientation selectivity, the orthogonal orientation usually is ineffective in eliciting any response whatsoever. Hence, while a good-size VESP is obtained via a counter-phasing chequerboard display, it is difficult to interpret its origins by receptive field theory. The use of a single orientation stimulus allows a more clear interpretation of the evoked potentials.

The small but distinct variations of receptive field size and retinal locus found by Hubel and Wiesel within an orientation specific column, suggest that no single straight line or group of parallel lines can be optimally aligned to large numbers of cells simultaneously. The positioning of the bar or edge stimulus is critical enough that it is quite reasonable to assume when one cell is optimally stimulated its

neighbors are not. Moreover, the intra-column variations did not follow any predictable pattern, but were randomly distributed among the cells within the column.

The two points derived above from the Hubel and Wiesel work lead to the following conclusions concerning the nature of an effective stimulus for the study of pattern vision. First, a field with a randomly generated luminance pattern should be capable of exciting large numbers of cortical cells provided it is composed of discrete luminance changes which combine to form randomly distributed regions of light and dark separated by distinct borders. The randomly oriented light and dark regions should be of an average size and distribution equal to the average receptive field size and distribution. Such a random pattern can be thought of as the superposition of uniformly oriented light and dark regions; that is, it is the random combination of many uniform patterns. Hence, it might be expected that each of the superimposed uniformly oriented patterns would stimulate cells optimally tuned and positioned to it more or less independently. As cell receptive field sizes and positions within a column tuned to a particular orientation are apparently randomly distributed within some narrow range, a random array of light and dark regions of similar distribution should optimally excite a good number of cells.

Now since whole columns of both striate and nonstriate visual cortex (Hubel and Wiesel, 1964) have been shown to be orientation specific in the cat, a series of stimuli representing single orientations either subtracted out of a random pattern or superimposed upon one, should allow the investigation of any orientation specific behavior that might

be demonstrable in a human VESP. Patterns having combinations of two orientations can be used to investigate the combinatorial aspects of the orientational specificity. Hubel and Wiesel (1964) in fact found some columns specific to two orientations orthogonal to each other; these were columns in non-striate cat cortex containing cells sufficiently more complicated in regard to their receptive field organization to warrant classification as hypercomplex cells. The finding that complex cells and hypercomplex cells comprise the entire population of non-striate visual cortex in the cat coupled with the conclusion of Jeffreys (1971) that the prominent human VESP peak is of non-striate origin focuses special attention on the details of the receptive fields for these cells.

Pollen (1975), found evidence that the complex cells of cat areas 17 and 18 are sharply tuned to respond optimally to particular spatial frequencies present in a visual stimulus. In area 17, receptive fields of complex cells were shown to be tuned to spatial frequencies in the range of 0.625-5.0 cy/degree. Area 18 cells tended to represent lower spatial frequencies. Pollen et al. (1971), proposed the hypothesis that complex cell responses might be encoding a Fourier spatial frequency transform over restricted regions of visual space. Blakemore and Campbell (1969), suggested much the same hypothesis for frequency selective channels in the human, based on psychophysical grating adaptation experiments. Hence, a further parameter of significance to a visual stimulus for human studies is suggested from the work of Pollen and others.

A preliminary description of a group of stochastically generated patterns which encompass the stimulus parameters of significance in animal experiments can now be formulated. The general pattern structure consists of randomly shaped light and dark regions of similar size. The elementary regions are oriented stochastically to generally line up in a particular direction. The reason for using statistically organized regions rather than uniform straight gratings is basically to accommodate the random staggering of receptive fields within an orientation specific column as described by Hubel and Wiesel (1964). Horizontal, vertical and diagonal orientations are individually represented in patterns of both high spatial frequency (small light-dark regions) and low spatial frequency (large light-dark regions), thereby forming a sub-group of 6 patterns. By taking patterns composed of regions arranged in two distinct directions at once, 12 more members of the group are defined. Finally, a 19th pattern consisting of regions with no overall orientation whatsoever is added for completeness. The details of the statistical generation of the patterns will be given in a later chapter. The logical starting point in using the patterns to test human vision is to consider their perceptual effect on prospective subjects. Hence, the work on human pattern recognition and discrimination is appropriately considered next.

Information from Human Psychophysics

The ability of animals and men to recognize and discriminate among visual patterns has long been recognized as one of the foremost achievements of the natural world. To put the problem in proper perspective, the example of Sutherland (1968) is pertinent. Assuming a visual

acuity of 1' of arc within a 10^0 radius of the fovea centralis, there are approximately 10^6 resolvable points available on the human retina for construction of a luminance pattern. If each point is allowed only two possible distinguishable light levels (black and white), than a total of $2^{(10^6)}$ different individual patterns can be constructed within the area centralis. These patterns can be categorized moreover, into $2^{(2^{(10^6)})}$ possible classes. Clearly, the 10^{11} - odd neurons in the human brain cannot code for more than a small fraction of all the possible classes of patterns the eye is likely to encounter in a normal working day. Various factors, still the subject of some controversy, including genetics, environment, survival, and so on are no doubt involved in the selection of the particular pattern classifications of importance to the visual system.

Some of the earliest perceptually significant pattern classes for primates including man have been those associated with the classical 'figure and ground' discrimination described by Hebb (1949), and those emphasized by the Gestaltist school (Koffka, 1935) involving uniformity and proximity factors within the visual field. A general class of patterns that can be described according to certain probabilistic rules has been separately designated one of the primary perceived attributes of an object; its texture (Metzger, 1926; Koffka, 1935). Richards (1974) has defined texture as an "attribute of a field having no components that appear enumerable". Many studies have been made concerning the statistical properties of a pattern which are responsible for its texture attributes (Jones and Higgins, 1945; Green, Wolf, and White, 1959; Julesz, 1962).

An important distinction is made between the general field of pattern recognition and the specific problem of texture perception. In performing a pattern recognition task, a test subject is typically allowed sufficient time to use all the intelligent facilities at his disposal. A rat in a maze for example can backtrack when he reaches a dead end and so forth. A spontaneous response, on the other hand, is expected in a texture discrimination problem. Usually subjects are not allowed close unlimited examination of the test stimuli. The exposure time for a pattern is usually carefully controlled in order to prohibit the use of involved cognitive processes quite unrelated to vision. The discrimination that is of interest to the texture perception problem is that which the eye performs almost instantaneously upon being exposed to a textured field. Julesz (1965) for example, constructed random-dot patterns by computer consisting of a large textured field in which a smaller field was imbedded. If the probabilistic rules that generated the two patterns were sufficiently different, an observer could detect the imbedded field at a glance. The ease with which such discriminations are performed by both human and animal subjects suggests this process, already a formidable task for modern computer-controlled electro-optical equipment, involves only quite primitive, neural mechanisms.

Julesz (1962, 1965, 1971) has performed extensive studies on the statistical processes which yield easily discriminable dot patterns. Julesz describes the statistical generators according to the order of the Markov process to which they correspond. Patterns which are generated by linear combinations of nearest-neighbor luminance are first order, patterns in which the product of nearest-neighbor values

is used to determine subsequent dot values are second order Markov chains, and so on. A pattern may also be generated from a combination of first order, second order, and higher-order statistics. Julesz found that first and second order statistical differences were a reliable index of the discriminability of two random dot patterns. When he attempted to extend his study to third order statistics and higher, Julesz (1965) obtained inconclusive results. In some cases, patterns with third order statistics do not elicit any perceptual differences, while in other instances, visual discrimination is facilitated.

Julesz concluded that the visual system was not in fact analyzing Markov chains as Green et al. (1959) had thought. Rather, complex statistical analysis of brightness distributions probably has little to do with texture discrimination. Julesz (1965) then turned to a study of the psychological clues to visual discrimination. He identified a kind of spontaneous preprocessing that extracts neighboring points which have similar brightness values and are perceived as forming clusters or lines. Julesz labeled this process "connectivity detection". He concluded that once the regions of like brightness were identified, texture discrimination then was performed according to the relatively simple statistics of these clusters and some description of them.

One simple property that has long been associated with a matrix of dots generated from some stochastic process is granularity. The extensive use of light-sensitive emulsions has promoted considerable research on the sources of graininess in photography (Jones and Higgins, 1945). Richards (1974) has investigated spontaneous texture

perception in terms of the spatial frequency spectrum of uncorrelated sinusoids required to match a given texture. The texture space consisted of all possible groupings of spatial sine-wave gratings in the range from 0.2-20 c/deg. oriented in a common direction and having an average contrast of 0.5. By limiting all his patterns to a common direction, Richards effectively eliminated the use of directionality differences in discriminating among members of the group. Of course, directionality or orientation is a strong clue to texture discrimination and this will be dealt with shortly. It was found that a suitable choice of only two or three frequencies used as "primaries" could provide good approximations to very complex patterns. That is, random superposition of many gratings of three different frequencies produced an acceptable match to a pattern composed of a flat spectrum of sinusoids from 0.2-20 c/deg. Richards proposed that perhaps three or four suitably chosen frequencies might be combined in ways to match all possible members of the texture space much in the way colors are matched by combinations of two or three primaries. Richards 'primary' textures were centered at 0.75, 2, 5, and 9.5 c/deg. He used a weighted superposition of the primary sinusoids to obtain his matches.

Here is a clear identification of the reduction of the enormous variety of random visual patterns into a small number of significant categories by the visual system. The relative amounts of each primary grating required to describe a given texture serve to somehow classify that texture in a way that is meaningful to the visual system. Here again, since no detailed inspection of the stimuli was performed by the subjects, the mechanisms involved in matching the textures were

probably primitive, spontaneous processes. Simple, straightforward descriptors of the visual input as Julesz concluded are here shown by Richards to be the basis for texture perception. Intuitively, a randomly generated unidirectional pattern elicits images ranging from very fine grained smoothness to very coarse clumpiness. In photography, the average size of the developed silver halide grain is used to classify a particular emulsion. Hence, there are numerous degrees of film granularity most of which are completely undetectable by the casual observer. The grain size index could be translated into a spatial frequency scale that would be at least as broad as the range used by Richards to define his texture space. The finding that such a wide range of granularity is compressed by the human into only three or four primary factors is then intuitively expected. Three or four psychological concepts of granularity are really quite sufficient to tell the observer all he cares (or needs) to know about a given one-directional random pattern. The finding that such psychological distinctions are performed spontaneously by the visual system without recourse to cognitive processes reveals the power of the underlying neural networks involved in texture perception.

The more general random patterns have, of course, a variety of orientation clues which add more dimensions to the texture space. The connectivity factor introduced by Julesz is closely linked to directionality. If dots in an array are connected by virtue of similar luminance, they must be connected in some direction or combination of directions. The results of neurophysiological studies previously mentioned emphasize the importance of orientation and point to a very

systematic organization of visual cortex according to orientation specificity. Evidence has been presented (Mansfield, 1974) on the relative importance of vertical and horizontal orientation as opposed to oblique. Psychophysical work on the normal human visual system (Attneave and Olson, 1967; Taylor, 1963) has also shown that horizontal and vertical lines or objects can be detected or discriminated more readily than obliquely oriented ones.

Beck (1972) considered the importance of the slopes of component lines in a patterned visual field to discrimination and similarity grouping. Beck distinguishes the spontaneous response of the visual system to stimulus differences under conditions of attentional uncertainty. He finds the orientation factors which produce similarity groups are also responsible for peripheral discriminability under uncertainty. Uncertainty here refers to the state of the visual system when attention is distributed over a patterned field. Beck found that horizontal and vertical discriminations were more easily performed than ones involving oblique orientations. He suggested that grouping occurs among descriptors based on their relation to the vertical-horizontal reference system: lines which correspond to the axes when attention is relaxed are more readily discriminated than those which do not so coincide.

The same sort of factors important to the responsiveness of individual cortical cells are also found to be critical to perception. The work of Richards and Beck begins to point toward the nature of perceptual organization concerning the discrimination clues. The psychophysical study reported in this thesis is also concerned with the specific rules used in perceptual classification and discrimination of the sig-

nificant clues in pattern vision.

The group of 19 random dot patterns arrived at from neurophysiological considerations encompasses the factors of significance for spontaneous texture perception. The three Cartesian orientations; vertical, horizontal, and diagonal are represented in both clumpy and smooth-grained patterns. Patterns with connectivity in pairs of the orientation directions are also included. Hence, not only can the relative strengths of the directionality and granularity clues be studied individually, but also the combinatorial rules governing these percepts can be described from experiments using the group of random patterns. It is thus possible to obtain a description of the interaction of granularity and directionality clues in spontaneous texture perception.

Summary

A group of random dot arrays has been described that is appropriate for use as visual stimuli from both psychological and physiological considerations. The evidence from experiments on the responsiveness of cells in visual cortex of cats and monkeys indicates a good deal of specificity for stimuli of characteristic orientations and shapes. Psychological testing has revealed the importance of certain orientations and of granularity in the processes of spontaneous texture perception.

Evoked potential studies on humans have resulted in the development of a stimulation technique (contrast-reversal) which has revealed response specificities akin to those obtained in animal work. Thus far, only uniform bars and chequerboard patterns have been used as contrast-reversal stimuli in VESP experiments. The results of

contrast-reversal experiments lead to the hypothesis that cheque patterns oriented according to some statistical rule would yield EP components correlated to the pattern statistics. Perceptual experiments on the human have indicated relationships of random array statistics to their discriminability. The question thus arises concerning the possible correlations of the key factors to spontaneous pattern perception with the components of the pattern-specific evoked potential.

The direction of this investigation is thus quite well defined by the choice of the stimulus group previously described. The details of VESP and psychophysical testing and analysis are the subjects of later chapters. Here the basic question of the study has been defined and can be formulated in the following hypothesis. Certain aspects of the human VESP for random dot patterns can be correlated to the perceptual clues used by the visual system in discriminating those patterns. If true, this hypothesis should provide an electrophysiological description of texture perception. The testing of this hypothesis is the purpose of the experiments to be presented in the next chapters.

III. EXPERIMENTS

The major experimental effort of this project was expended on the recording of scalp potentials from relatively large electrode arrays on a limited number of human subjects. Typically, arrays of 20-30 electrodes were placed in a given experiment via plexiglass mounting helmets individually molded to the shape of each subject's head. The reason for multiple electrode recording is to facilitate the study of fluctuations in scalp potential distribution during the time-course of a VESP. Special protocols of scalp preparation and electrode placement had to be developed to allow effective recording with the helmets. Moreover, a pattern alternation apparatus, as described in Chapter II, which could be driven synchronously from the data collection system, was designed and constructed. Control of stimulus presentation and data collection was accomplished via a PDP-11/20 online digital processor.

As a means of interpreting VESP results, psychophysical tests were performed, psychophysical test apparatus and protocol were devised, and a particular group of stimuli was constructed. The stimuli, a group of random dot patterns, were produced by a stochastic process designed to yield textures representative of the qualitative factors found by Julesz and other to be significant to the texture discrimination task. The results of unit recordings in visual cortex by Hubel and Wiesel, Pollen, and other neurophysiologists also contributed to the definition of the stimulus group as described in Chapter II.

Mathematical Generation of the Textures

In Chapter II, a group of 19 textures was defined according to the properties of directionality and granularity. The basic quality underlying these factors is that identified by Julesz as connectivity. The correlation between dots in our test patterns is a convenient device to control the global property of connectivity in the array rather than using a more rigorous definition of connectivity between dots as done by some authors (Minsky and Papert, 1969). We now define correlation among dots in a given direction according to classical principles. Let the dots be limited to two possible brightness values, white or black, only. For each dot, i , we define a variable, S_i , which assumes one of two possible values depending on whether dot i is white or black. If dot i is white, $S_i = +1$; if dot i is black, $S_i = -1$. Now the various order brightness correlations ($C_1, C_2, \dots, C_j$) among N dots in a row along a particular direction can be calculated by applying the formulas below.

$$C_1 = \frac{1}{N} \sum_{i=1}^N S_i \quad (3.1)$$

$$C_2(\Delta) = \frac{1}{N-\Delta} \sum_{i=1}^{N-\Delta} S_i S_{i+\Delta} \quad (3.2)$$

$$C_j(\Delta_1, \Delta_2, \dots, \Delta_j) = \frac{1}{N-\Delta_j} \sum_{i=1}^{N-\Delta_j} S_i S_{i+\Delta_1} S_{i+\Delta_2} \dots S_{i+\Delta_j}$$

$$\Delta_1 < \Delta_2 < \dots < \Delta_j \quad (3.3)$$

The subscripts, j , refer to the order of the correlation and Δ signifies the proximity of the correlated dots; i. e. $\Delta = 1$, nearest neighbors, $\Delta = 2$, second nearest neighbors, etc. The first order correlation is simply the algebraic sum of the S_i 's divided by N . Hence, C_1 varies from -1.0 if all dots are black to +1.0 if all dots are white. C_1 then indicates the average brightness of the entire row of dots but tells nothing of the relative groupings of whites and blacks. The connectivity parameter we are interested in controlling is involved with the higher order correlations $C_2, C_3 \dots$ etc. C_2 gives the averaged sum of cases in which two dots separated by a positional increment, Δ , have similar brightness minus the cases where the two dot brightnesses are different. Let the case of the i -th and the $i + \Delta$ -th dots being of different brightness be defined as a transition. Then C_2 can be rewritten as simply the probability of a non-transition minus the probability of a transition.

$$C_2(\Delta) = \left[\frac{1}{N-\Delta} \sum_{i=1}^{N-\Delta} |S_i S_{i+\Delta}| \right]_{S_i=S_{i+\Delta}} \text{ minus } \left[\frac{1}{N-\Delta} \sum_{i=1}^{N-\Delta} |S_i S_{i+\Delta}| \right]_{S_i \neq S_{i+\Delta}} \quad (3.4)$$

$$C_2(\Delta) = P_{NT} \text{ minus } P_T \quad (3.5)$$

Since the two cases of transition or non-transition are all inclusive, their probability must add to unity.

Thus:

$$P_{NT} = 1 - P_T \quad (3.6)$$

$$C_2(\Delta) = 1 - 2P_T \quad (3.7)$$

Likewise, the first order correlation is just the difference between the probability of a dot being white ($S_i = +1$) and the probability of it being black ($S_i = -1$). Again these cases are all inclusive.

$$C_1 = \left[\frac{1}{N} \sum_{i=1}^N |S_i| \right]_{S_i=+1} \text{ minus } \left[\frac{1}{N} \sum_{i=j}^N |S_i| \right]_{S_i=-1} \quad (3.8)$$

$$C_1 = P_w \text{ minus } P_B \quad (3.9)$$

$$\text{But: } P_w + P_B = 1 \quad (3.10)$$

$$\text{Therefore: } C_1 = 2P_w - 1 \quad (3.11)$$

Having established the above relations for correlation in terms of absolute probabilities, we may now develop the specific case of $C_1=0$ and $\Delta=1$ which is the desired situation for the stimulus group. In other words, the desired dot arrays must consist of 50% white dots and 50% black dots with sufficient nearest neighbor second order correlation, $C_2(1)$, to produce the required directional connectivities. A large amount of nearest neighbor correlation in a given direction will result in well connected strings of dots in that direction. Negative $C_2(1)$ will tend to break up the connectedness. From general considerations, the total positive or negative second order nearest neighbor correlation, $C_2(1)$, was set at $\pm 1/3$. This value results in patterns with clearly discernible structure. In cases where connectivity in two directions is specified simultaneously, $C_2(1)$ was set to $\pm 1/6$ in each of the two directions.

The actual method of generating the patterns on the computer involves picking numbers out of a random process that has a known probability distribution, expected value, and standard deviation. A

range of values is set based on the probability distribution such that, if a value within the range turns up, the current dot in the pattern being generated will be white, and if the random process yields a number outside the set range, the dot will be black. In this manner, many patterns having identical generating statistics but quite different individual dot values can be created. Computer random number algorithms usually require some arbitrary starting value and will produce a different sequence of numbers for each different starting value. Thus, by generating patterns with identical statistics but quite different local dot configurations, any subject response unique to the local arrangement of dots on a particular slide will be averaged out.

Now in order to set the cutoff points for determination of dot brightness from values picked out of a random process, the probability for each dot being white or black must be known. The necessary probabilities are determined from the specified correlations C_1 and C_2 . Let us say a texture with significant vertical connectivity but zero connectivity in either horizontal or diagonal direction is required. The requirements translate into the following second order directional correlations as shown in Table 3.1.

$$C_2(1) = 1/3 \left| \begin{array}{l} \text{vertical} \end{array} \right. \quad C_2(1) = 0 \left| \begin{array}{l} \text{horizontal} \\ \text{diagonal} \end{array} \right.$$

The probabilities which are set by the second order correlations are the conditional probabilities that determine the value of a contiguous dot in a particular direction given that the previous dot in that direction was a certain value. Since we are dealing with either

Texture #	Correlation Description	Vertical Correlation	Horizontal Correlation	Diagonal Correlation
1	pV	.333	0	0
2	nV	-.333	0	0
3	pVpH	.167	.167	0
4	nVnH	-.167	-.167	0
5	pVnH	.167	-.167	0
6	nVpH	-.167	.167	0
7	pH	0	.333	0
8	nH	0	-.333	0
9	pHpD	0	.167	.167
10	nHnD	0	-.167	-.167
11	pHnD	0	.167	-.167
12	nHpD	0	-.167	.167
13	pD	0	0	.333
14	nD	0	0	-.333
15	pVpD	.167	0	.167
16	nVnD	-.167	0	-.167
17	nVpD	-.167	0	.167
18	pVnD	.167	0	-.167
19	R	0	0	0

Table 3.1 Correlation description of the 19 stimulus patterns

white or black dots, the conditional probabilities are defined as follows:

P_+ = probability of next dot being white given previous dot was white

P_- = probability of next dot being white given previous dot was black

Since we have C_2 defined in terms of P_T , the probability that a brightness transition will occur between the current dot position and the next one, an expression for P_T in terms of P_+ and P_- is needed. The total probability of events leading to a transition is summed as follows:

$$P_T = P_w(1+P_+) + (1-P_w) P_- \quad (3.12)$$

$$P_T = P_w(1-P_- - P_+) + P_- \quad (3.13)$$

where $1-P_+$ = the probability of the next dot being black given previous dot was white

$1-P_w$ = overall probability of the starting dot being black

Then substituting equation (3.13) into equation (3.7) for C_2 , we obtain the following equation:

$$C_2(1) = 1-2P_w + 2P_w P_- + 2P_w P_+ - 2P_- \quad (3.14)$$

Now we have decided that the first order correlation in all our arrays should be 0 so that there will always be a 50/50 mixture of white and black dots. Thus, the overall probability of any dot being white or black is determined.

$$C_1 = 0 = 2P_w - 1 \quad \text{thus } P_w = \frac{1}{2}$$

With $P_w = \frac{1}{2}$ equation (3.14) for C_2 becomes:

$$\begin{aligned} C_2 &= 1-2(\frac{1}{2}) + 2(\frac{1}{2})P_- + 2(\frac{1}{2})P_+ - 2P_- \\ &= 1-1+P_- + P_+ - 2P_- \end{aligned}$$

$$C_2 = P_+ - P_- \quad (3.15)$$

Thus, we are able to get one equation for P_- and P_+ from the definition of C_2 . A second equation is required if we are to solve for specific values and it is obtained by defining the overall probability of a given dot being white, P_w , in terms of the conditional probabilities P_+ and P_- .

$$P_w = P_w P_+ + (1 - P_w) P_- \quad (3.16)$$

Solving (3.16) for the relationship between P_+ and P_- in terms of P_w we obtain:

$$P_+ + P_- \left(\frac{1}{P_w} - 1 \right) = 1 \quad (3.17)$$

Hence, we see that our choice of $C_1 = 0$ which resulted in $P_w = \frac{1}{2}$ also requires the following to hold:

$$P_+ + P_- = 1 \quad (3.18)$$

From equations (3.15) and (3.18) the conditional probabilities in each direction for the desired vertical connectivity texture can be calculated as follows:

$C_2 = 1/3 = P_+ - P_-$ $1 = P_+ + P_-$ Thus: $P_+ = 2/3$ $P_- = 1/3$	$C_2 = 0 = P_+ - P_-$ $1 = P_+ + P_-$ Thus: $P_+ = 1/2$ $P_- = 1/2$	horizontal diagonal
vertical		

For this vertically connected pattern, we see that the conditional dependence of a given dot on its horizontal and diagonal neighbors is $\frac{1}{2}$ or chance probability. Thus, in generating the pattern we need only

consider the polarity of the previous vertical dot to determine the probability of white for the next dot to be generated. For patterns in which connectivity in two directions simultaneously is desired, we must consider the previous dots in both directions. By doing similar analyses for each of the 19 patterns in the test stimulus group qualitatively defined in Chapter II, we obtain the probabilistic rules for their computer generation.

The computer generation of the 19 textures proceeds as follows. Two adjacent sides of the texture matrix are filled with white and black dots by chance probability. Starting at the corner defined by the filled sides, subsequent dot positions are filled by determining the probability of white for the next dot from the polarities of the previous dots in the directions prescribed by the probabilistic rule for the given texture being generated, and then picking a number out of a random process. If the number picked is within the probability range for white, the next dot is made white, otherwise it is black. Each time a texture is started, a different random order is used to fill the starting sides. Hence, the random process is given a different starting point for each generation cycle.

Slides are made for the texture matrices using graphics routines which control the beam on a cathode-ray tube film exposure system. The system generates 35mm black and white frames. Each frame can be mounted as a 35mm slide. The 100 x 100 texture matrix is made up within the addressable CRT matrix by drawing filled-in squares where a white dot is required or leaving a position blank where a black dot is specified.

Thus, the conceptual qualities of connectivity, granularity, and directionality are quantitized. The quantities are translated into probability tendencies which are used to set cutoff points on the values picked from a random process. Finally, computer graphics yields the finished results for our stimulus group as shown in Fig. 3.1.

Psychological Tests

Having created the test pattern group, an experiment to determine perceptual discriminability among members of the group was devised. The object of the discriminability experiment was to obtain measures of intra-group proximities so that a so-called 'scaling' analysis could be applied. Often perceptual tests are designed in such a way that the subject has a good deal of freedom in performing the required discriminations (Julesz, 1962). For example, the subject may be allowed free examination of each object in the group simultaneously for as much time as he likes; he is then asked to rank order them on a scale of 1 to 10 from most alike to most different. Such a procedure may be quite acceptable when the objects are of a complex nature and one is interested in studying discriminations made by the higher cognitive processes. In dealing strictly with the visual system however, it is imperative to structure the test in such a way that higher cognitive processes have a minimal effect on the responses. The most direct way of restricting the use of the logical thought mechanisms is by presenting the stimulus for only a brief exposure time and requiring a simple quantitative response shortly thereafter. In fact, the exposure/response paradigm should be done repetitiously at

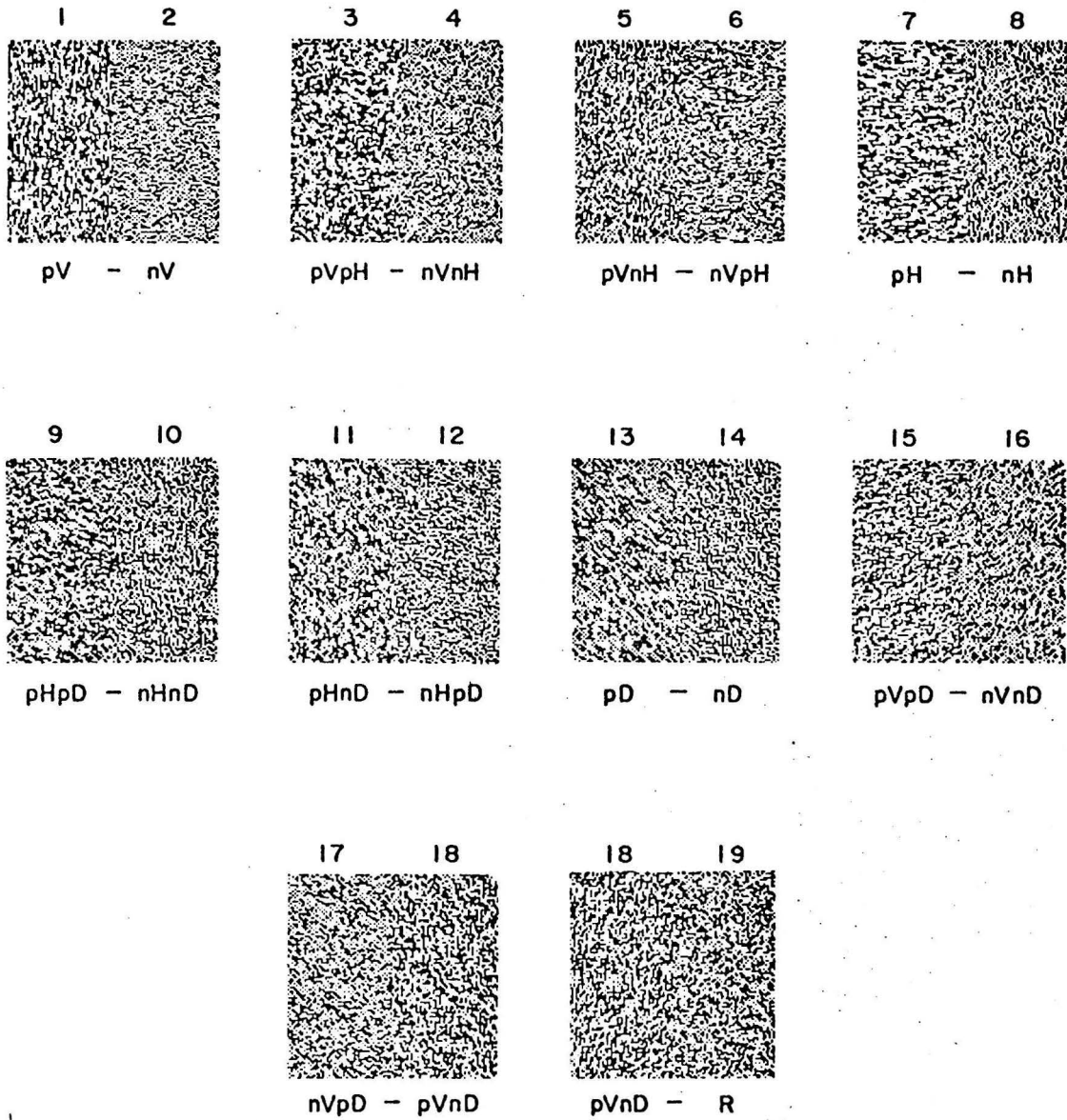


Fig. 3.1 Group of 19 texture stimuli in pairs

a good rate (1 every 4 or 5 sec) so that the subject relegates the function to a simple reflex act requiring minimal conscious supervision. The task must be simple, unambiguous, and self-contained in the sense that each repetition is a complete entity not requiring information from previous ones for its performance. By observing all the conditions just enumerated, the experimenter can justify the contention that he is indeed measuring a relatively simple stimulus-response function and that his subjects are not outwitting his test.

Now instead of asking for a qualitative estimate by the subject concerning how different a given pattern is from the other members of the group, it is necessary to devise some discrimination task whose performance will yield a measure of discriminability. Since the task must be self-contained and not draw on previous exposures, it must involve more than one member of the stimulus group simultaneously. One possibility would be to display two patterns side by side and ask the subject if they were the same or different. Theoretically the average number of times a subject said two different patterns were the same would be a measure of discriminability. Besides requiring an active search for differences in the patterns, this test is unsatisfactory since it is cumbersome to arrange that there be equal probability of the two patterns being the same or different. For the 19 pattern group, there are 190 possible pairs, only 19 of which contain two of the same pattern. To have equal numbers of identical pairs and different pairs, 342 pairs would be required. Thus, while displaying objects in pairs is an attractive scheme, the 'same/different' task presents some problems.

The tests reported here utilized a boundary orientation task as a measure of the discriminability between two patterns shown simultaneously. The pair of patterns were oriented either side by side or one directly above the other. The subject's task was to identify the orientation of the boundary between the two patterns by writing either "V" for vertical or "H" for horizontal on his answer sheet. This task asked the subject nothing about his opinion of the differences between the two patterns displayed; rather, it was assumed that if he perceived distinct differences, he would be able to successfully perform the task. Hence, the subject was not instructed to compare two patterns cognitively, but to perform a simple visual task which nevertheless, required that he be able to discriminate the patterns.

The apparatus required to perform the psychophysical tests are the following: A set of 190 slides containing the 19 test patterns taken two at a time, a slide projector, a means for controlling the slide duration time, and a fixation device so subjects could be prepared to observe the brief slide exposure. The slides were generated according to the statistical rules for each member of the group. Each slide consisted of a square matrix of 100 x 100 dot positions of which the left 100 x 50 rectangle was filled according to the rule for one texture and the right 100 x 50 area was filled according to the rule of the second texture. Nineteen slides in which the two halves came from the same texture rule were included in the 190 slides.

According to the test plan, half of the slides were rotated 90 degrees so that the two texture rectangles were at the top and bottom; hence, the boundary between textures could be either vertical or hori-

zontal. Since the textures were generated on the matrix with a left-right orientation, a 90 degree rotation of the slide effects a 90 degree change in the texture identity. For example, texture 6 is given in Table 3.1 as $C_V = -.167$, $C_H = .167$, $C_D = 0$, but if it is rotated 90 degrees its description is $C_V = .167$, $C_H = -.167$, $C_D = 0$, which is the same as texture 5. Naturally, the identity conversions for each orientation had to be accounted for in the processing of the data so that the directionality labels 'vertical', 'horizontal', and 'diagonal' would retain their conventional meaning in the visual field.

The test slides were randomly ordered with half of them rotated 90 degrees and arranged in 6 slide projector trays. Each tray contained a maximum of 36 slides. The projector could be remotely operated. An approximately elliptical mask with smooth boundaries defined the borders of the slide illumination in the projector and hence the projected image. An electronic shutter, also remotely controlled, positioned immediately after the exit aperture of the projector lens allowed the required control of image exposure duration. The shutter was normally closed and when triggered would open for precise, adjustable exposure times of 1, 1/2, 1/4, 1/8 sec.

The tests analyzed herein were performed on three subjects well experienced in the theoretical aspects of the experiments and the textures and also experienced in viewing the textures freely at their leisure and under the test restrictions. These subjects, therefore, had developed a routine reaction mechanism for the test which was based on a knowledge of the underlying theory.

Protocol

The test subjects were seated in a dimly lighted room approximately 20 feet from a large white projection screen. The average luminance of the central portion of the screen with no image projected on it was 6 foot-Lamberts. A narrow black boundary coincident with the image circumference on the screen provided a fixation region for the subjects before the image was displayed. At the 20 foot viewing distance, the image subtended an angle of approximately 10 degrees. The exposure time was 1/2 second.

Subjects were seated at the viewing distance and given data sheets. The luminance of the white data sheet on each subject's desk was approximately 14 foot-Lamberts. The subjects were instructed to fixate within the image boundary delineated on the screen; they were told an image of two textures arranged either side by side or one above the other would appear briefly and they were to respond with their very first impression of the boundary orientation between the textures by writing either a V for vertical or an H for horizontal in the appropriate box on the data sheet as quickly as possible. Each slide tray was run off as a unit. On a start signal, subjects fixated, the image was displayed for 1/2 sec., and the subjects were allowed 3-5 seconds to mark their answer sheets and refixate for the next trial. The 6 trays of 190 slides were run with a short break between each tray followed by a second run of the 6 trays in a different order. Thus, two runs through the entire 190 slides would be performed in one sitting that lasted usually on the order of 20 minutes. The complete experiment consisted of 10 sessions over a period of one month.

The random order of the slides and their orientation was changed twice during the 10 sessions at the 4th and 8th session. Thus, the final data set consisted of 3800 responses from each subject which represented 20 trials for each pair of the 19 textures oriented both vertically and horizontally. The vertical/horizontal orientation for individual slides was chosen randomly before the first session on the basis of a 50% distribution of verticals and horizontals. When the orientation was changed at the 4th and 8th sessions, it was done by merely rotating all slides 90 degrees and then reidentifying the connectivity orientation in each texture. Thus, 50% of the slides (and of course, the texture identities) were shown oriented vertically on sessions 1-3 and 8-10 and oriented horizontally on sessions 4-7. Therefore, half the 190 texture pairs were shown oriented vertically in 6 sessions, or 12 total exposures, and horizontally in 4 sessions, or 8 total exposures. Likewise, half the texture pairs had 12 horizontal and 8 vertical exposures. The three subgroups of sessions 1-3, 4-7 and 8-10 are convenient for studying stability of the data, effects of learning and effects that may be unique to a particular slide in a certain orientation.

Raw Data

Following a test session, the data sheets for each subject were hand checked against a master and the errors for each texture pair were recorded. At the end of the 10 sessions, the total wrong answers out of the 20 exposures for each texture pair were converted to a number representing the perceptual difference between the two textures according to the following rule.

$$\text{Perceived Difference} = (|\text{number wrong} - 10|)/10$$

The basis of the conversion rule is the assumption that if a subject could perform the discrimination task correctly on only half the trials on average (10 wrong answers out of 20 chances), he was simply guessing and could actually see no difference between the textures. Hence, ten wrong answers result in a zero score using the Perceived Difference (PD) formula. The formula gives the same score for a given number of errors above or below 10. Twenty wrong out of twenty trials for example, would yield the same maximum possible PD of 1.0 as none wrong out of twenty. An error rate significantly greater than 50% however, surely indicates something is wrong with the particular slide or the test itself. There were only 13 cases of error rates greater than 50% out of the 513 data points for the three subjects (excluding the points for slides containing identical texture halves). Investigation of the 13 suspicious cases revealed that most problems involved unique patterns formed at the texture boundary on a particular slide or by the superposition of the asymmetrical fixation border masking the projected image.

The 13 cases of high error rate along with the data for slides of both half textures the same were excluded from further analysis. Otherwise, a stability analysis over the 10 sessions showed only a small error rate decline of 10-15% for the three subjects, which was due no doubt, to improvement of the various capabilities required by the test.

The raw data matrices for each subject are shown in Fig.3.2. The matrices are lower-half, diagonal absent. Each number represents the perceptual difference between the two textures designated by its row and column indices in the matrix. Hence, the matrices

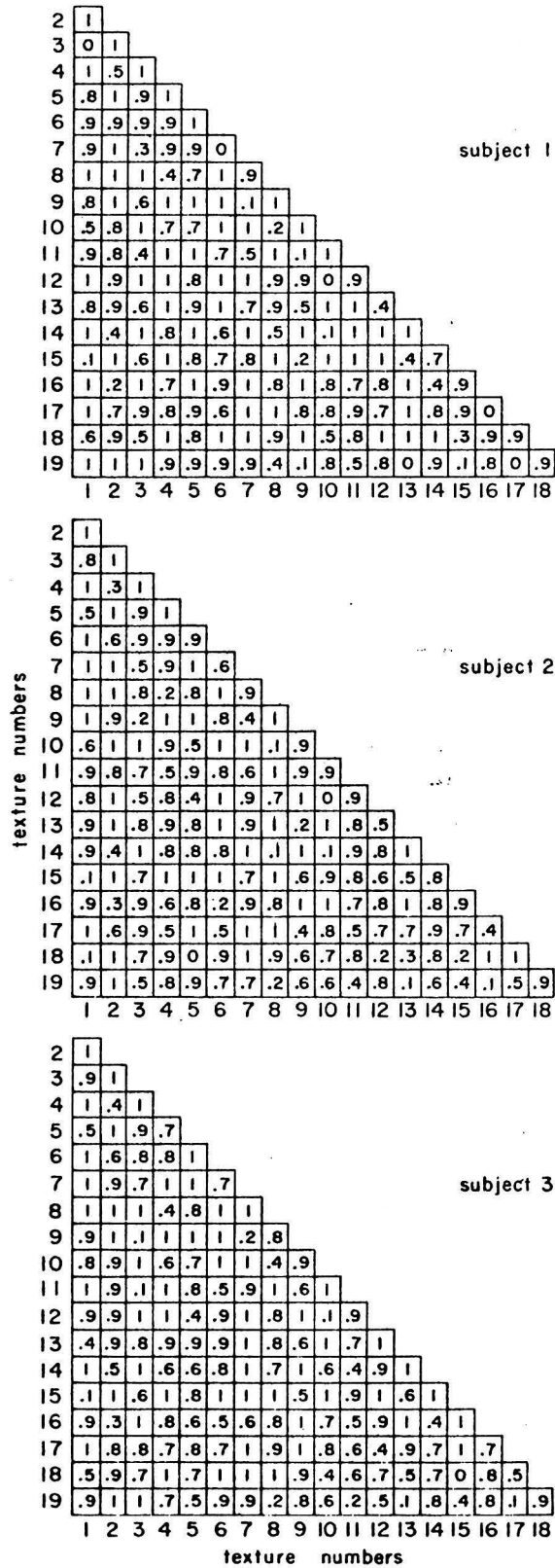


Fig. 3.2 Dissimilarity matrices for 3 subjects

represent the dissimilarity within the stimulus group. A close comparison of the matrices for each subject reveals a fairly high amount of correlation. On average, two patterns confusable for one subject tend to be confusable for all other subjects. Clearly, some systematic mathematical technique is required to further analyze the grouping of stimulus patterns represented by the raw data matrices. As subgroups are formed of objects different from all the other objects but quite similar to each other, some rationale for the groupings based on a knowledge of the characteristics of the objects can be formulated. The study of the raw data matrices will be taken up in a later chapter following the introduction of the analysis technique known as scaling.

Electrophysiological Tests

The measurement of electrical activity originating within the brain via electrodes affixed to the scalp is a challenging problem from both technical and theoretic aspects. The junction of a metal electrode and a physiological preparation presents as complex an electrolysis and ion transport system as any electrochemist would care to approach. The amplification and recording of signals from scalp electrodes necessitates the use of differential amplifiers with low noise and high impedance characteristics that are quite demanding even by current standards. The recovery of coherent signal out of noise many times greater than the signal requires a considerable amount of processing expertise.

The study of evoked potentials as opposed to on-going or spontaneous scalp activity requires that all the above problems be dealt with and additionally that a stimulus of known, controlled character-

istics be applied to the sense modality under study. Having decided from a review of the literature to stimulate with an alternating phase display, the design and implementation of such a display had to be accomplished.

The Counter-Phase Generator

Monocular stimulation in Maxwellian view was chosen as the stimulus mode. Maxwellian view allows the optimal utilization of source illumination and facilitates subject fixation. Computer generated 35mm slides of the dot patterns were chosen for the objects to be imaged since they provided very accurate, repeatable displays of the dot patterns. In fact, it was found that both positive and negative phases of each texture had to be computer generated and then processed on the same run of 35mm film to obtain positives and negatives which fit each other perfectly. Simply generating slides of all the textures and then shooting contact negatives of them did not produce positive-negative pairs with perfect fit.

An electro-optical feedback scheme was required as the means of modulating the phase of the final image. The optical system for the counter-phase generator is shown in Fig. 3.3. A 100 watt quartz-iodide tungsten filament lamp (Osram) fed by a regulated power supply is the source of continuous illumination. Two separate optical systems image the source through diffusers onto aperture plates where the uniform images are chopped. Following the aperture plates, the images are collimated and the two collimated beams are superimposed through a pelicle beam splitter. The ultrathin membrane pelicle was required in order to eliminate problems of double images caused by reflections

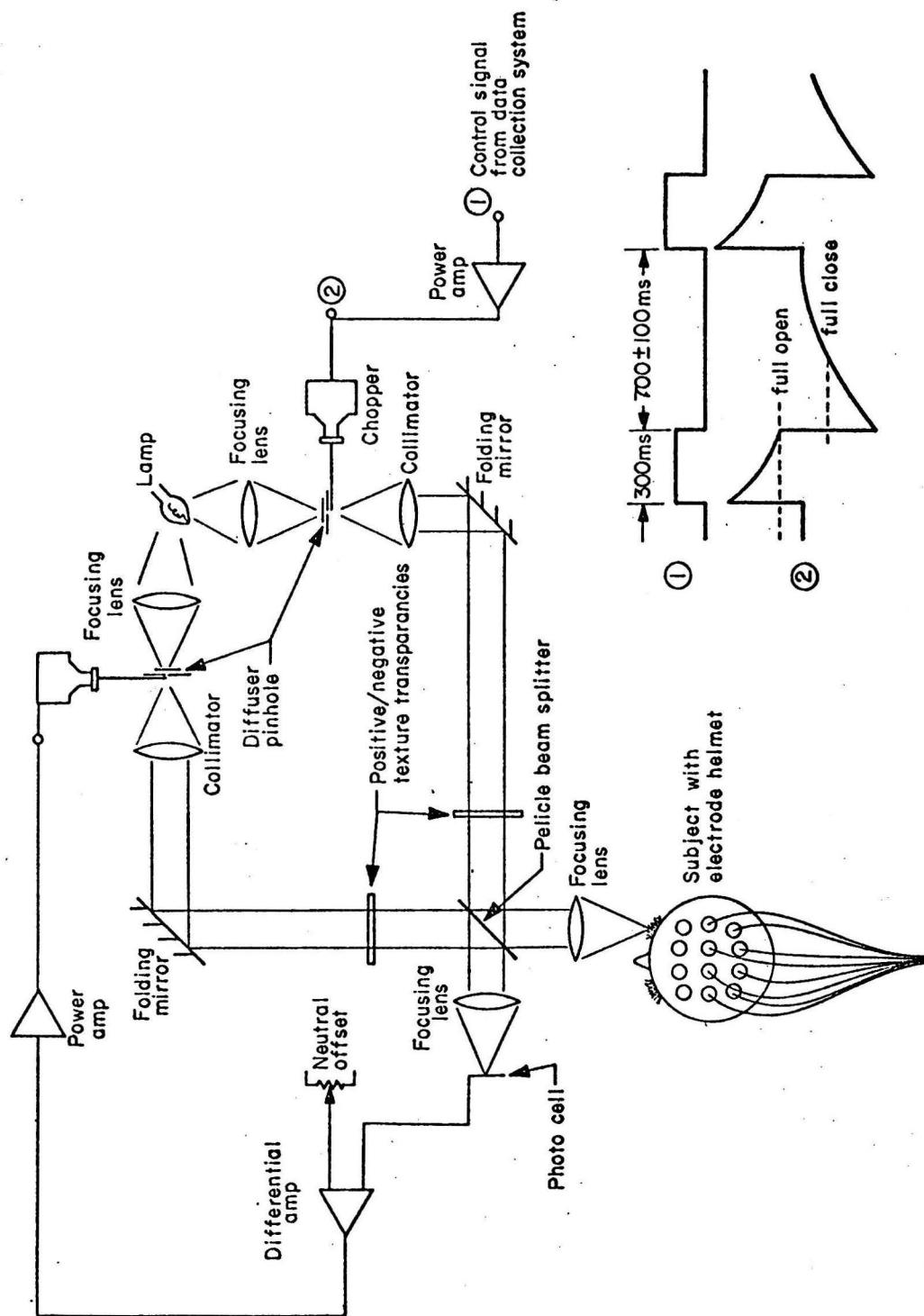


Fig. 3.3 Electro-optical schematic for counterphase generator.

from the relatively wide spaced front and back surfaces of ordinary half-silvered mirrors. The two output beams from the pelicle are reimaged onto a silicon solar cell detector to provide a feedback path to drive the system and the entrance pupil of the subject.

In the electronics which control the two optical choppers to produce the antiphase stimulation, Darlington current drivers are used to provide the required power to the choppers (Ling Dynamic Systems). Capacitive coupling was used in order to allow bi-directional current drive to the units. Each chopper blade is set to cut off just half of its respective aperture when no signal is present. Current in one direction thus drives the blades so as to completely close each aperture while current in the opposite direction completely opens each aperture. The blades can be driven beyond the extent of the apertures.

One weakness of the circuit design is the use of capacitive coupling rather than two transistors in push/pull configuration to provide bi-directional drive to the choppers. The capacitors place an effective low frequency limit on the system which depends on the value of capacitor used. Physical size considerations resulted in the use of capacitors which allowed repetition rates of not much slower than 2 per second. The discharge time of the driver circuit as used in the experiments of this report is on the order of 250 ms. This is to say that by 250 ms following the onset of a pulse which either completely opens or closes an aperture, the chopper blade will have receded 63% of the way back to the neutral, half-open position. While the coupling technique does have low frequency limitations, the discharge to the neutral position behavior has advantages for certain stimulus modes as will

be discussed later.

As shown in the optical diagram, one chopper stage is driven by signals from the data collection system while the other is controlled by the amplified signal from a solar cell receiving the superimposed images of the positive/negative texture pair. The superposition of the two images when both chopper blades are at the neutral (half-open) position will yield a uniform field of constant brightness. The signal generated by the solar cell for neutral chopper position is bucked at the input of a differential amplifier by the voltage on a potentiometer. The potentiometer voltage is adjusted so that the amplifier output is precisely zero for the neutral condition of both choppers. Hence, with no drive to the control chopper, the feedback chopper is also left in neutral.

When a signal is applied to the control chopper, the total illumination to the solar cell changes accordingly. As an example, let the control chopper be driven completely open, increasing the illumination on the solar cell by 1.5X. the cell responds with a large signal which is amplified and sent to the feedback chopper in a direction so as to decrease the light on the cell. For this example the feedback chopper would be driven closed thus reducing the total illumination on the cell to the original neutral value. Thus, the system operates via the feedback path to dynamically maintain the illumination on the solar cell (and thus the illumination to the subject) at a constant level.

The Maxwellian view optics has a maximum usable field of approximately 20 degrees. The current 35 mm slides have circular patterns of 16 mm diameter and subtend approximately 10 degrees.

Fixation circles subtending 1 degree and positioned at the center of the texture are generated on the slides. The overall illumination to the subject is variable. For the subjects used in these tests, a comfortable brightness setting was in the range of 10-12 ft-Lamberts. Since there are 100 possible dot positions across the diameter of the texture circle, each individual dot composing the texture subtends approximately 0.1° or 6 min. of arc. Thus, individual dots are well above the visual resolution limit. Although the dot and no-dot sizes of positive/negative pattern pairs match exactly, the observer is still able to discern a fine mesh pattern when both slides are illuminated simultaneously. A set of micrometer controlled XY stages holds the slides and allows separate positioning of either of them for best alignment to the other. Changing of slides and subsequent realignment is easily performed by the test subject himself.

In considering the details of counterphase stimulation as reviewed in Chapter II, it was decided to use square wave alternation at a low repetition rate. The scheme of using both pattern appearance/disappearance and phase reversal seemed to offer a good chance of evoking scalp potentials specific to the statistical characteristics of the patterns. Now the low frequency behavior of the chopper circuitry provides a simple way of obtaining a pattern appearance stimulus. Starting from the neutral position, an 'on' pulse to the control chopper will cause the immediate appearance of the texture out of the previously uniform field. If the pulse is sufficiently long (600-700 ms), the texture will fade out to the neutral uniform field condition. By overdriving the chopper past the aperture it will remain totally open for

200-300 ms and the texture will be displayed at a constant level.

Thus, the response to the appearance event can be recorded for 200-300 ms following the event without fear of any changes occurring in the stimulus. Alternatively, if a comparison of pattern reversal to pattern appearance responses is desired, an 'off' trigger to the control chopper can be applied 200-300 ms following the 'on' trigger thereby causing a pattern reversal. A scheme such as the one just described was used in most of the experiments reported herein. The timing diagram in Fig. 3.3 shows the time course of stimulus events. Starting from the neutral field condition, the pattern appears, stays constant for about 300 ms while the appearance response is sampled at 4 ms intervals, the pattern then reverses and the reversal response is sampled for 300 ms. After sampling the reversal, a random interval of dead time lasting 400 ± 100 ms is interjected by computer control to allow the choppers to fall off to the neutral field conditions, and for any evoked activity to subside.

Hence, the stimulus events are: pattern appearance from uniform field; constant pattern; pattern reversal; constant pattern; pattern fades to uniform field. Only the response during the periods of constant pattern immediately following an appearance or reversal event is sampled and recorded by the data collection system. This sequence of stimulus events thus allows the close examination of any differences in the scalp potentials evoked by pattern appearance and pattern reversal events. The systematic study of responses from the two stimulus events for patterns of known statistics and perceptual characteristics should reveal any pattern specific behavior present in those responses.

The Electrode Placement Technique

As explained in previous chapters, the source localization

analysis approach to the study of scalp potentials has as its first requirement the collection of data from many scalp positions simultaneously. Hence, we were faced with the problem of placing a good number of scalp electrodes. The basics of the electrode/scalp interface have of course, long been mastered by practiced EEG clinicians. Standard silver-silver chloride electrodes capable of bi-directional current flow (bipolar) which can be either glued or taped to the scalp are readily available in various shapes and sizes. The placement of standard electrode arrays of the sizes required for our analysis (20-30 electrodes minimum) is in fact not outside the capabilities of the experienced clinical technician. The task is nevertheless, a formidable one for both experimenter and subject alike.

Our solution to the problems of electrode placement and subject comfort is the construction of tailor-make plexiglass helmets, air-conditioned for comfort and molded to the subject's head. Detachable rubber disks provide the tension for holding electrodes in place while pin-connectors mounted on the helmet allow the easy connection of a wire harness once all electrodes have been secured. A pictorial history of the construction of a helmet is shown in Fig. 3.4. Once a shell is produced, electrode holes are drilled, pin connectors are mounted, and an air-conditioning hose and rubber gasket are attached.

Bipolar $A_g : A_g Cl$ electrodes must be in good contact with an electrolyte in order to function properly; the electrolyte must itself saturate the epidermis at the recording site. Bi-directional flow paths for ions must exist to accommodate the full dynamic range of scalp potentials which can be as large as $\pm .3 - \pm .5$ mv. Of course, these



FIG. 34 HISTORY OF HELMET CONSTRUCTION.

voltages are developed by a current limited source thus requiring very high input impedance at the amplifier so as not to load the source and distort the signals. The low frequency nature of the signals causes further complications and accentuates the problems at the electrode/scalp interface.

Although workable EEG recordings are obtained even today with outdated vacuum-tube differential amplifiers, the extremely high input impedance field-effect transistor (FET) has produced major improvements in signal to noise ratio of amplified scalp voltages which are essential to the study of evoked potentials. Now in order to utilize the full input impedance (on the order of $10^9 \Omega$) of state-of-the-art semiconductor devices, direct coupling of electrode to amplifier is required. Any intervening capacitive coupler imposes the need for a d.c. biasing circuit on the input stage. The biasing circuit shunts the a.c. impedance of the amplifier and thereby precludes the full realization of the high device input impedance. Thus, the careless designer is left with an amplifier of pedestrian characteristics which may incorporate a superb FET-input device that is not fully utilized.

Now, when d.c. coupling is used in the electrode/amplifier connection, the static charge situation on the electrode becomes crucial. An improperly coated electrode poorly attached to dry outer epidermal layers can easily develop several millivolts of static charge. Such a static level, because of the d.c. coupling, would most likely drive the input stage well into saturation if it has any gain at all.

Now it is no secret among practiced clinicians that optimum recordings are obtained when the scalp has been carefully cleaned of

all dirt, dry flaky skin, oils, etc. and well permeated with a electrolytic paste. Of course, a major obstacle to the proper preparation of the scalp recording site is hair. Standard clinical procedure is to shave off all or part of the subject's hair. The experiments reported herein were performed on the author himself and other members of the Vision Research group; subjects who cannot in all cases be described as cooperative. Shaving the scalp was therefore, not seriously attempted for these subjects. The presence of hair is thus the single major reason for the continual loss of several electrodes in any given session and subsequent problems of comparing results from different sessions.

Having determined to deal with the problem of hair by less than extreme measures, a protocol was developed whereby electrodes could be placed using a mounting helmet with a reasonable percentage of success. The procedure goes as follows. The helmet is placed on the subject's head initially with electrode holes open allowing each electrode site to be marked on the scalp with a marking pencil. The helmet is then removed. Now that each site on the scalp has been identified, the task of cleaning and preparing it proceeds. Preparing the scalp involves scraping the dry dead epidermal layers down to moist fresh skin. One of the new motor-driven tooth brushes with extra-hard bristles was found to be extremely effective in this regard. Next an electrolyte paste is rubbed firmly into the skin and a small dime-size pad of paste built up at the electrode site. Care must be taken not to short out two or more sites with paste. The Grass EC-2 paste tends to limit the shorting problem between electrodes and also to hold each electrode rigidly in place thus, alleviating mechanical

noise problems.

Once each electrode site has been prepared, the helmet is again mounted on the subject and each electrode (also coated with a dab of paste) is secured to the scalp site by attaching the rubber mounting disks to the holes on the helmet as shown in Fig. 3.5. The electrodes used on the helmets are specially built for mounting in the rubber disks as shown in Fig. 3.6. Several lengths of electrodes have been produced to allow for variations in the distance between the scalp and the outer surface of the helmet. The entire procedure for mounting 20-30 electrodes with a helmet-fixture can be accomplished in less than 2 hours by a practiced technician. It is recommended that the subject be given some reading material or other diversion to occupy him during what initially could be considered something of an ordeal. After a few sessions with the helmets, most subjects become quite tolerant and are able to comfortably participate in over an hour of experiment time.

Once the electrode array has been mounted, the subject is seated in an electrically shielded room where the wiring harness from the pre-amplifiers and a vacuum line for air conditioning are attached to the helmet. The vacuum sucks cooling air through the helmet which, in addition to being a great source of comfort, neatly solves the problem of perspiration from the scalp shorting out the electrodes. The subject is next aligned to the optics of the particular experiment, power is switched to the amplifiers, and the recording session is under way.

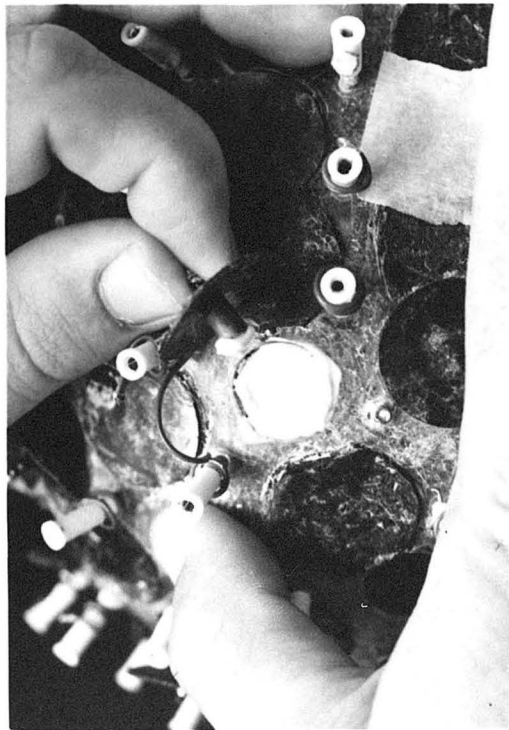
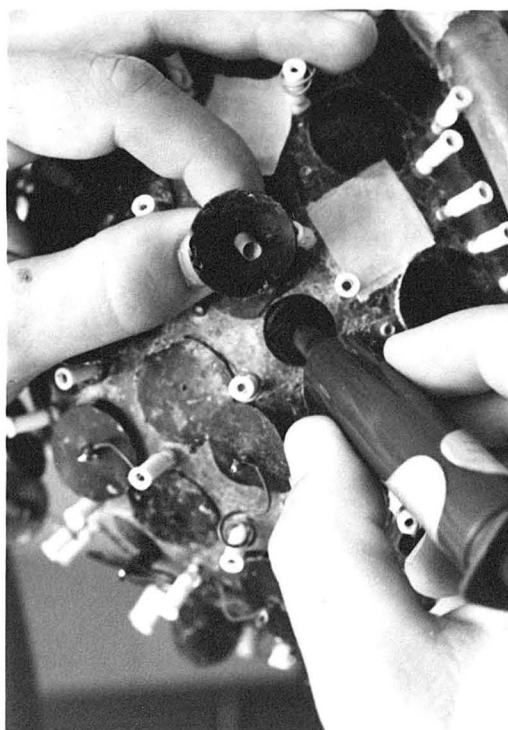
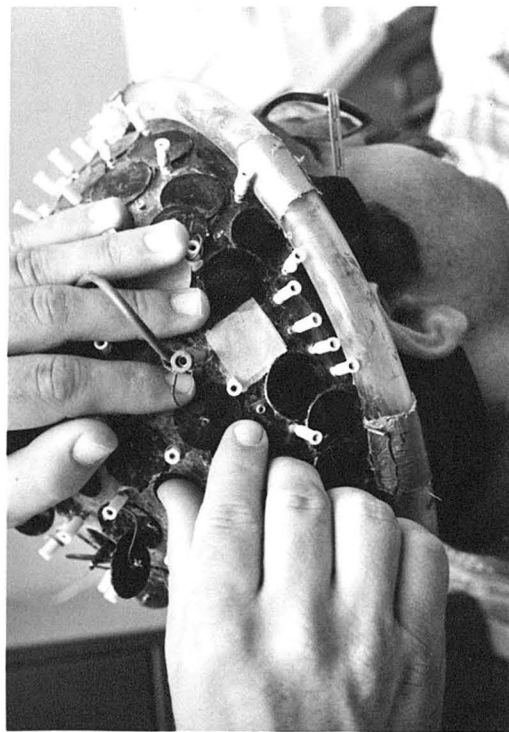


Fig. 3.5 Steps in electrode placement technique with a mounting helmet.

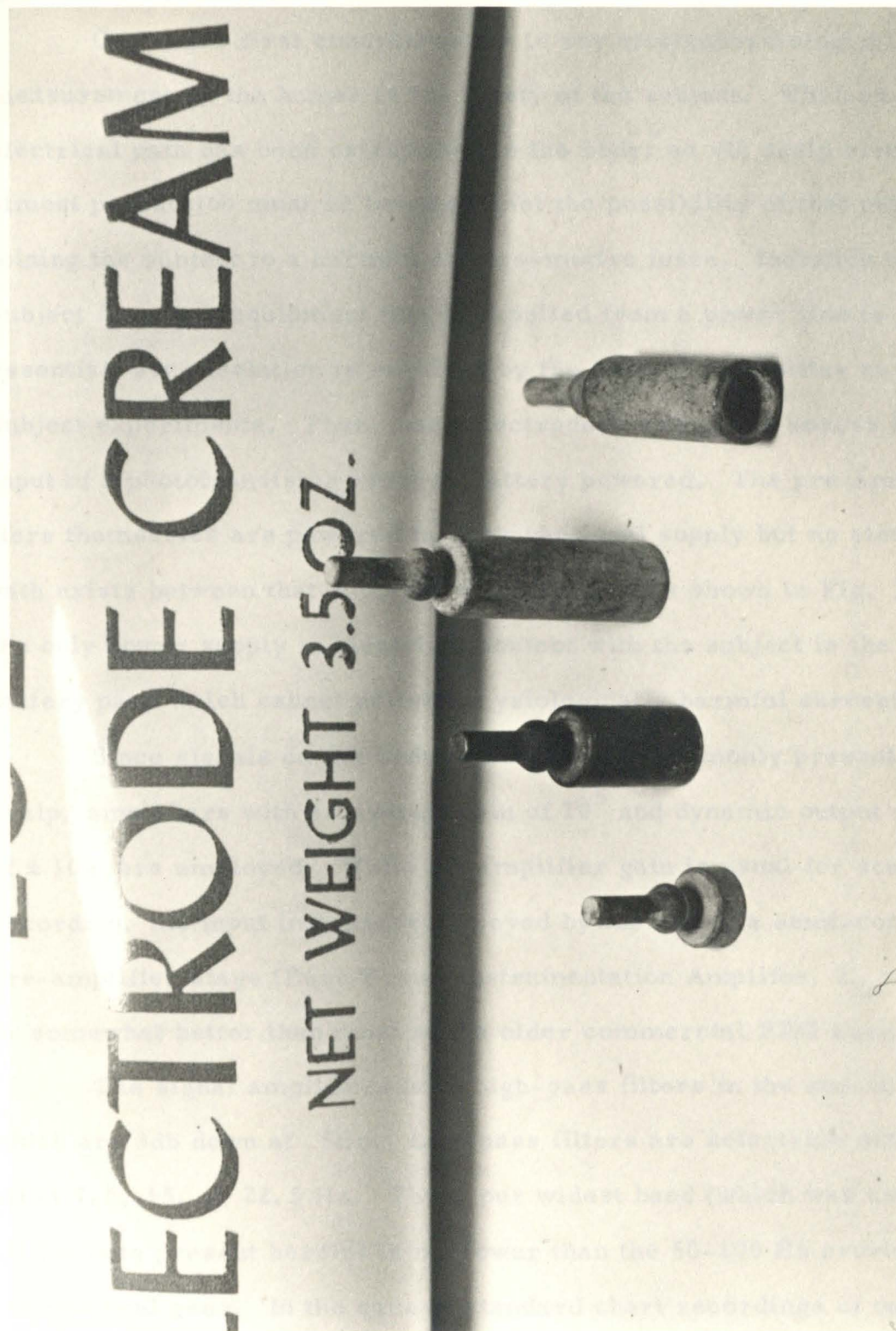


Fig. 3.6 Variety of electrode sizes.

Signal Amplification and Collection

One of the first considerations in any electrophysiological measurement on the human is the safety of the subject. When an electrical path has been established to the body, as via scalp electrodes, utmost precaution must be taken against the possibility of that path ever joining the subject to a harmful electro-motive force. Isolation of the subject from any equipment that is supplied from a power line is essential; such isolation is required by the Caltech committee on human subject experiments. Thus, each electrode is connected across the input of a phototransistor which is battery powered. The pre-amplifiers themselves are powered by a conventional supply but no electrical path exists between that supply and the scalp. As shown in Fig. 3.7, the only power supply in electrical contact with the subject is the battery pack which cannot deliver physiologically harmful current.

Since signals on the order of $100\mu\text{v}$ are commonly present on the scalp, amplifiers with an overall gain of 10^5 and dynamic output range of $\pm 10\text{v}$ are employed. While the amplifier gain is usual for scalp recording, the input impedance achieved by the use of a semi-conductor pre-amplifier stage (Burr Brown Instrumentation Amplifier, $Z_{\text{in}} = 10^9\Omega$) is somewhat better than most of the older commercial EEG equipment.

The signal amplifiers have high-pass filters in the second stage which are 3db down at .5Hz. Low-pass filters are selectable with cut off at 7.5, 15, or 22.5 Hz. Thus, our widest band (which was used for all the data present herein) is narrower than the 50-100 Hz provided by conventional gear. In the case of standard chart recordings of ongoing EEG, the signal bandwidth of the recording pens is the overall band-

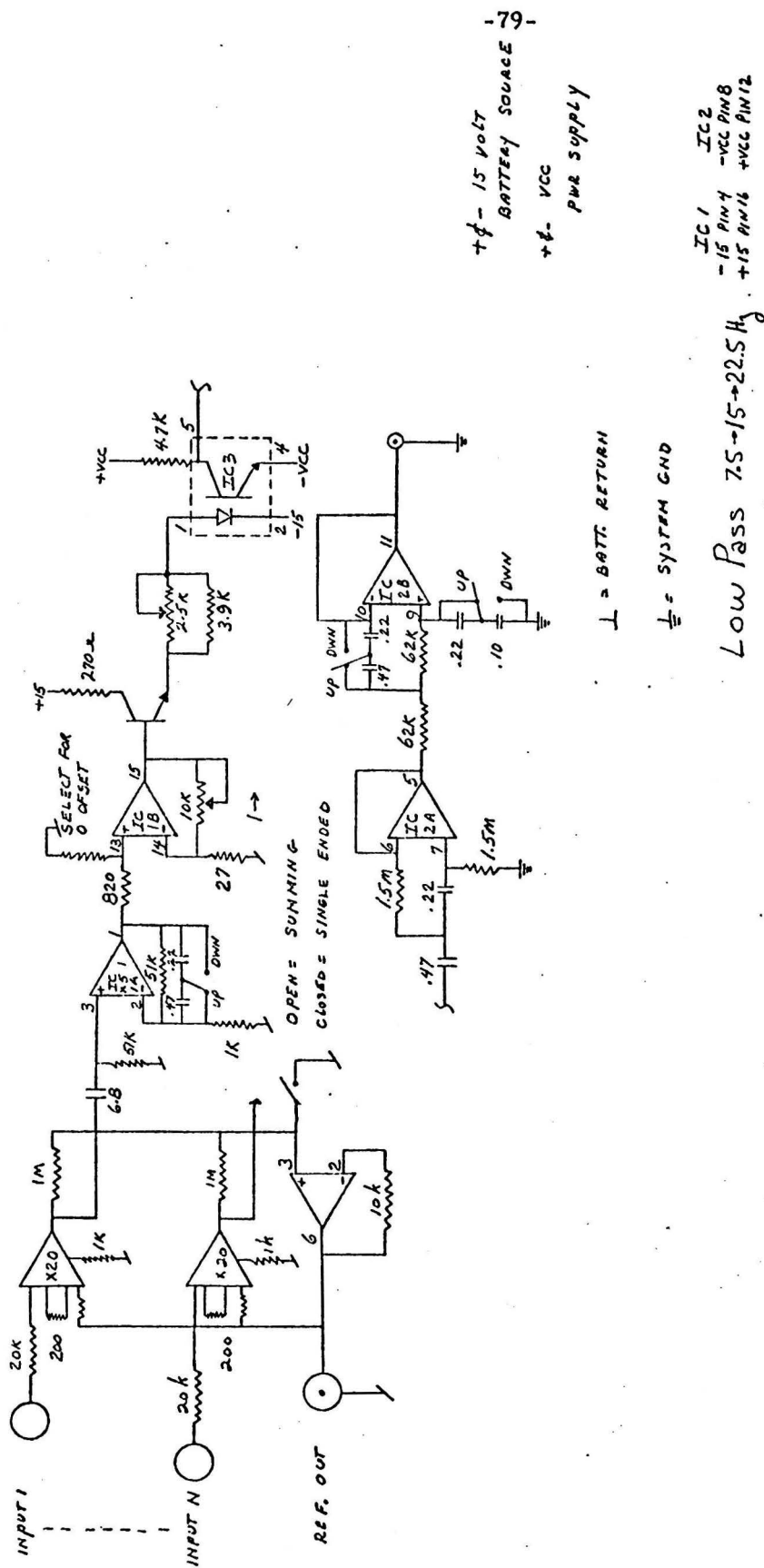


Fig. 3.7 Circuit diagram of EEG amplifiers showing opto-isolators, referencing modes, and filters

width delimiter for the system. Often, in the interest of conserving paper, chart recording systems are band-limited at 30-50 Hz so that any higher frequency signals (or noise) presented by the electrode amplifiers are attenuated in plotting. Since most clinicians have standardized on the use of only one or two varieties of recording system and plotting speeds, they are usually able to compare and interpret data of like bandwidth. While ongoing scalp potentials can contain frequencies in the 100-1000 Hz range, these signals have as yet found little clinical usage.

In the early stages of experimentation, an effort was made to determine the optimum filter for VEP recording based on the classical Wiener theory (Papoulis, 1965). The least squares error criterion requires the minimization of the following error function:

$$e^2 = \int_0^T [s(t) - \hat{s}(t)]^2 dt \quad (3.18)$$

where $s(t)$ is the true signal of interest over the recording epoch 0-T and $\hat{s}(t)$ is the minimizing estimation of that signal. The Wiener derivation for the optimal recovery filter $R(f)$ yields:

$$R(f) = \frac{W_s(f)}{W_s(f) + W_n(f)} \quad (3.19)$$

where $W_s(f)$ and $W_n(f)$ are the energy spectra of the signal and noise during the epoch. Unfortunately, the two spectra required to determine $R(f)$ were found to be extremely difficult to define in practice.

VEP spectra were calculated using a fast fourier transform algorithm for data from several sources (Lehmann, et al., 1969). On average,

good flash-evoked potential data was found to have quite narrow spectra that peaked sharply at 7-10 Hz. Estimation of noise spectra is extremely dependent on experimental conditions. Well placed electrodes properly equilibrated are less noisy than those which have not been properly attached. Of course, ongoing scalp activity is noise as far as VEP signals are concerned. The spectra of ongoing activity varies widely according to the subject's mental state and hence is difficult to estimate.

The equation for the optimal filter can be rewritten in terms of the ratio of signal to noise spectra (S/N) at a given frequency, f, as follows:

$$R(f) = \frac{S/N}{1 + S/N}$$

At most frequencies S/N is much less than 1. Usual evoked potentials are on the order of 5-10 microvolts while ongoing scalp signals are in the hundreds of microvolts. R(f) is approximately proportional to S/N at most frequencies, so that a simple guide to picking R(f) is that the lower the overall noise becomes, the wider the recording band can be made. When noise dominates the signal at higher frequencies, it makes sense to eliminate those frequencies from the signal estimation.

Because of the aforementioned variability involved in the noise of any evoked potential experiment, it was decided to provide a range of upper frequency cutoff points on the amplifier filters. The experimenter could then decide on the optimum bandwidth for the amplifiers based on the characteristics of the ongoing scalp activity during a particular recording session. The three cutoff points chosen were based

on a compromise between ideal points for different noise estimate and points that could be easily realized within such limitations of the amplifiers as coupling, biasing, and physical size. Three-pole break points were used in order to sharply define the various frequency bands. Sixty db per decade roll-off filters were also dictated by the optimization formula because of the rather narrow spectra of VEP signals.

Ultimately, it was found that when noise conditions were so severe as to require narrow band (7-1/2 Hz) filters, resultant VEP's were significantly smaller than those taken with wide band filters with the same number of stimulus repetitions. Moreover, phase shifts introduced by the narrow band filters distorted latencies of various signal components which required further processing to correct. Thus, only data taken with the wide band (22-1/2 Hz) filters were processed completely through the various stages of analysis.

The signal amplifiers could be operated in one of two referencing modes as shown in Fig. 3.7. The supply voltage common point is attached to the subject via an electrode on the vertex. It is necessary that amplifier bias voltage be referenced to the same datum point as input signal. The differential inputs of each amplifier may also be referenced to the single electrode at the vertex of the head as is the usual clinical practice. Alternatively, the outputs of each amplifier are summed and can be fed back through a unity gain amplifier to the reference input of each differential stage. As discussed in Kavanagh(1972) the summing reference is possible with large electrode arrays since in theory, the total potential on the surface of the head should remain constant. About half of our experiments were done in summing mode

and half in single reference mode. VEP's obtained with either mode under constant experimental conditions were found to be within the limits of reproductability of both modes. Equipotential maps produced from data in either summing or reference mode were also very similar.

On the other hand, the level of background activity seemed to be dependent on the choice of reference mode. Usually, potential fluctuations were smaller in summing mode although this was not always true. Presumably, the instantaneous difference between two electrode sites on average should be greater than the difference between either site and the sum of all the activity on the scalp. Hence, the choice between single reference and summing reference modes often was based on the subjective appearance of the ongoing scalp activity in the two modes.

The first procedures following amplifier turn-on thus involve inspection of several electrode channels and setting of bandwidths and referencing mode for the recording session. The remainder of the session is under on-line computer control and usually proceeds quite smoothly and automatically. The protocol consists of typing in such parameters to the PDP-11/20 as stimulus duration interval, interval standard deviation, number of repetitions, and a description of the stimulus pattern being displayed. All this information is echoed on a teletype by the 11/20 and the stimulus/recording run is initiated. Thus, at the end of a session, the experimenter has a magnetic tape containing one file of serially multiplexed digital data for each stimulus run and a hard copy print out of the stimulus and recording param-

eters for each file. A typical recording session using pattern appearance/reversal stimuli might consist of 7 runs of 100 repetitions per run on each of 3 different texture patterns to make a total of 21 separate files on the data tape.

The preliminary stage of data processing involves taking median values of the recorded potentials at each sample instant over the total number of stimulus repetitions for each run. Next the median evoked potential (MEP) epochs are digitally filtered by a fast fourier transform (FFT) technique. The FFT algorithm first extracts the signal components at 4, 8, 12, 16, 20, and 24 Hz from the MEP epoch. Then an inverse transform uses the aforementioned components to recreate the MEP waveform. The FFT scheme was adopted early in our work when it was found that a considerable amount of extraneous fluctuations could be removed from the waveforms with a minimal amount of peak amplitude loss and no phase shift by using this digital filtering technique.

Following digital filtering, means and standard deviations are calculated for each group of 7 MEP runs made on the same stimulus texture. Such averaged median evoked potentials for one electrode are shown in Fig. 3.8. Each of the 3 groups of traces in Fig. 3.8 is the mean of seven runs for one texture and the mean plus and minus one standard deviation at each sample instant. The sample instants are at 4 ms intervals and span the immediate 256 ms period (64 samples) following the appearance and reversal stimulus events. The occurrence of the two stimulus events is marked on the graphs. Directly beneath or nearly coincident with each set of 3 MEP traces

ELEC #17

$\frac{1 \mu V}{.17 ms}$

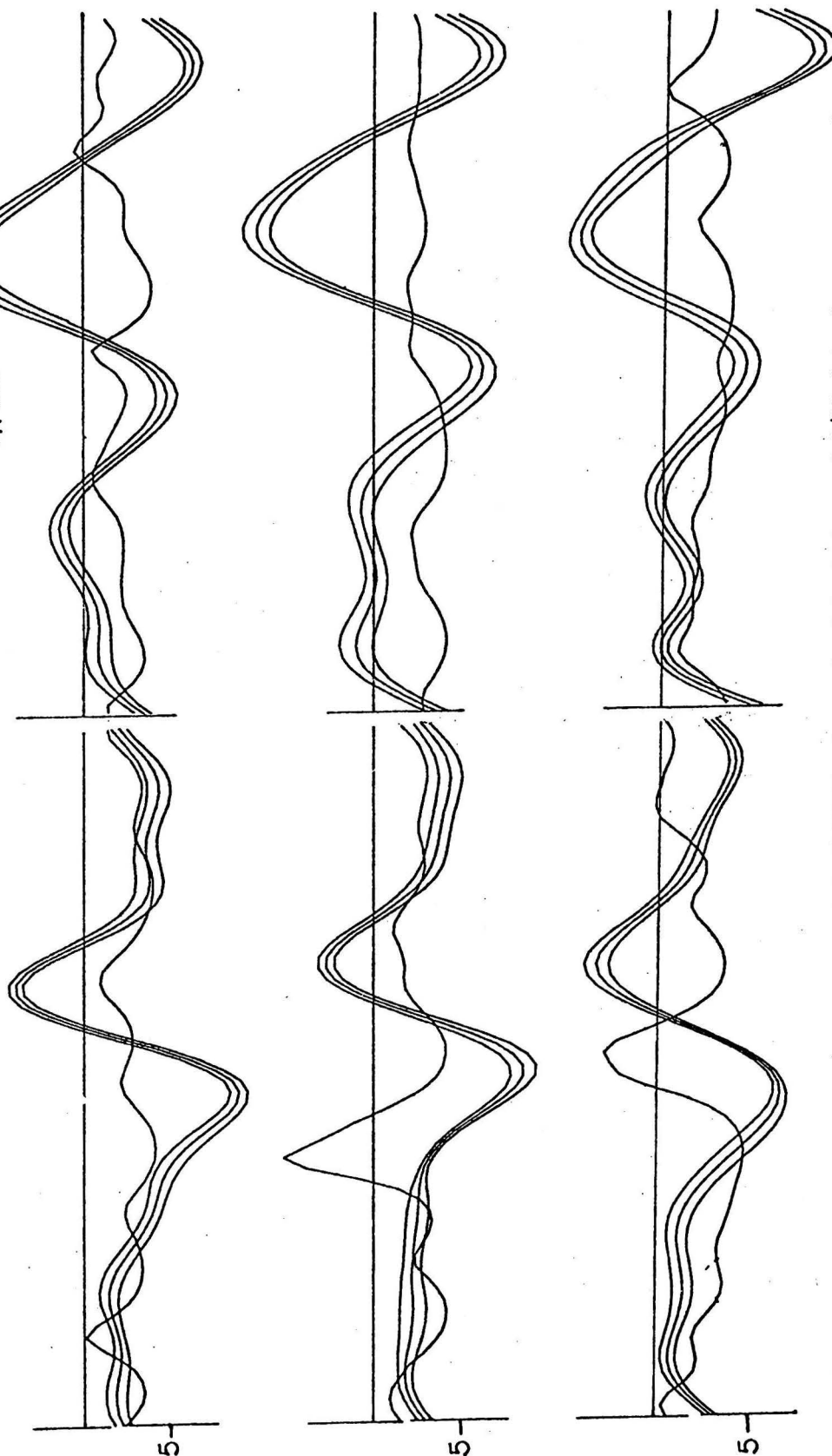


Fig. 3.8 Median evoked potentials (MEP) $\pm$ 1 standard deviation and S/N Sub. 3 appearance and reversal, Tex. #1, #2, and #7.

is a curve denoting the RMS signal to noise ratio (S/N) at each sample instant.

The RMS S/N is calculated by dividing the standard deviation at each sample point into the RMS value of the mean signal over the entire recording epoch. The S/N is a useful measure of the overall quality of the signal on a given electrode. Moreover, S/N values are used for weighting purposes in our analysis as will be discussed in the next chapter. The MEP groups and S/N curves for 22 electrodes of one experiment on subject 3 are shown in Fig. 3.9. In Fig. 3.10 the positions of the 22 electrodes on the subject's head and the average S/N for each electrode is shown schematically. The electrodes with high S/N are in the occipital region centered about theinion as should be expected for visually evoked potentials. Figs. 3.11 - 3.14 show complete electrode traces, S/N, and scalp locations for data sets from one experiment each on subjects 2 and 1. These three data sets, typical of a number of experiments run in our labs on the three subjects used in texture discrimination tests, will be analyzed by the technique of equivalent source localization in Chapter V where they will form the raw data for that analysis.

Here we may make a visual comparison of the MEP traces to determine if any significant results are immediately obvious. Comparison of traces between subjects shows subject 3 to have quite different MEP's than subjects 1 and 2. Subject 3's MEP's are quite symmetrical in terms of the appearance/reversal response amplitude and latency. The reversal response shows two negative-going peaks as opposed to just one for the appearance response. This 'doubling' of

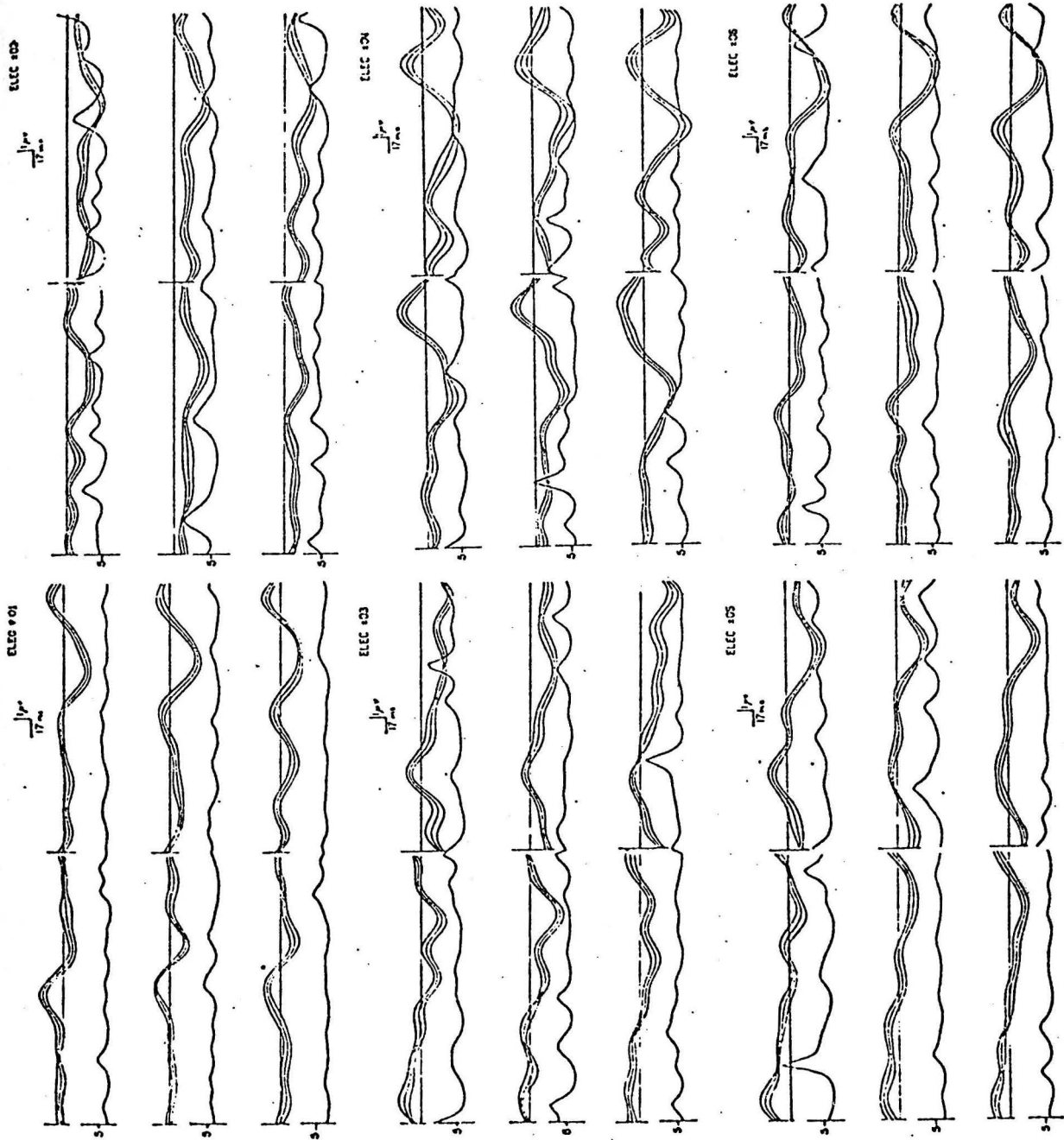


Fig. 3.9a MEP and S/N traces. Sub. 3 Tex. #1, #2, #7 electrodes 1-6

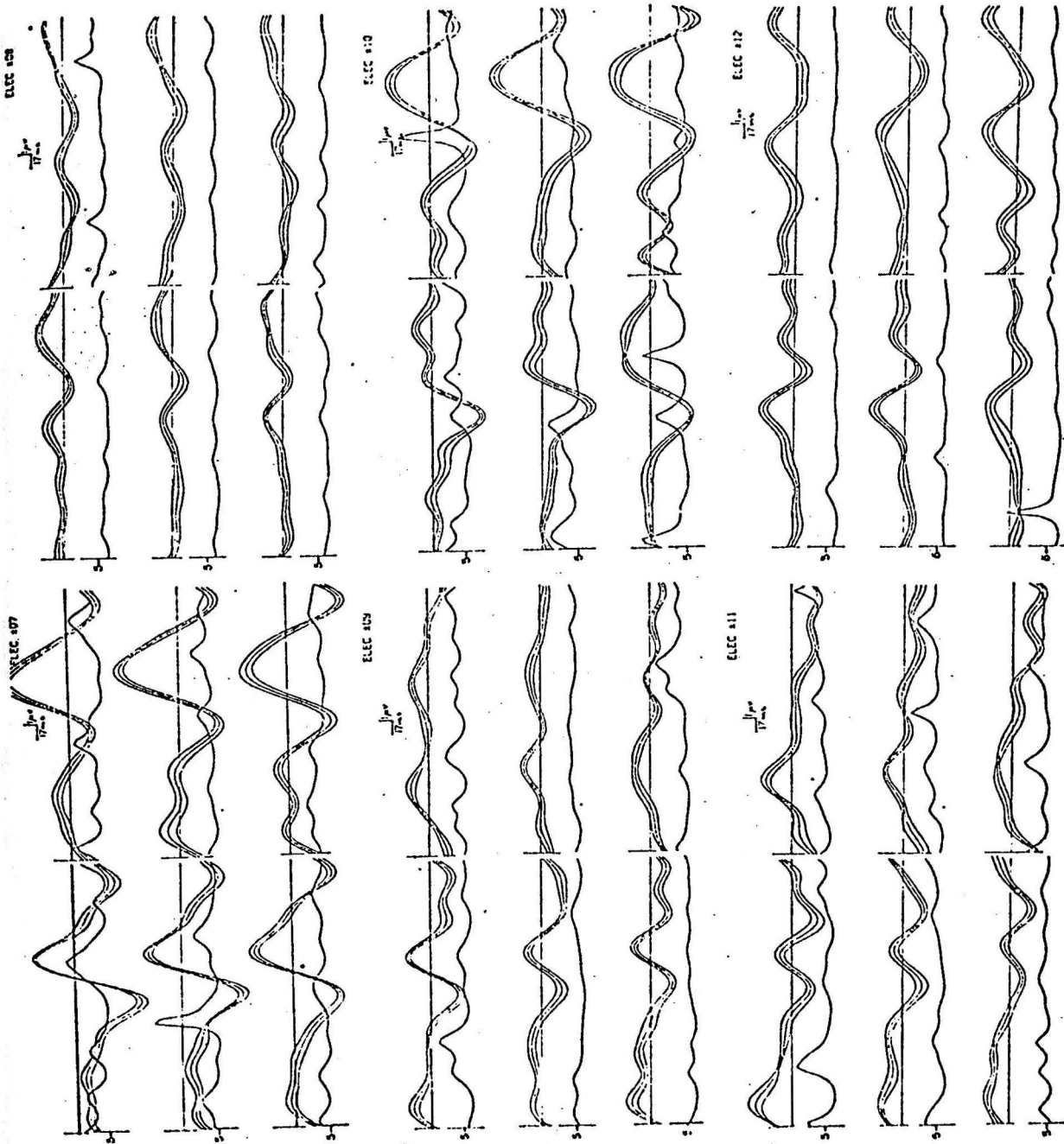


Fig. 3.9b MEP and S/N traces. Sub. 3 Tex. #1, #2, #7 electrodes 7-12

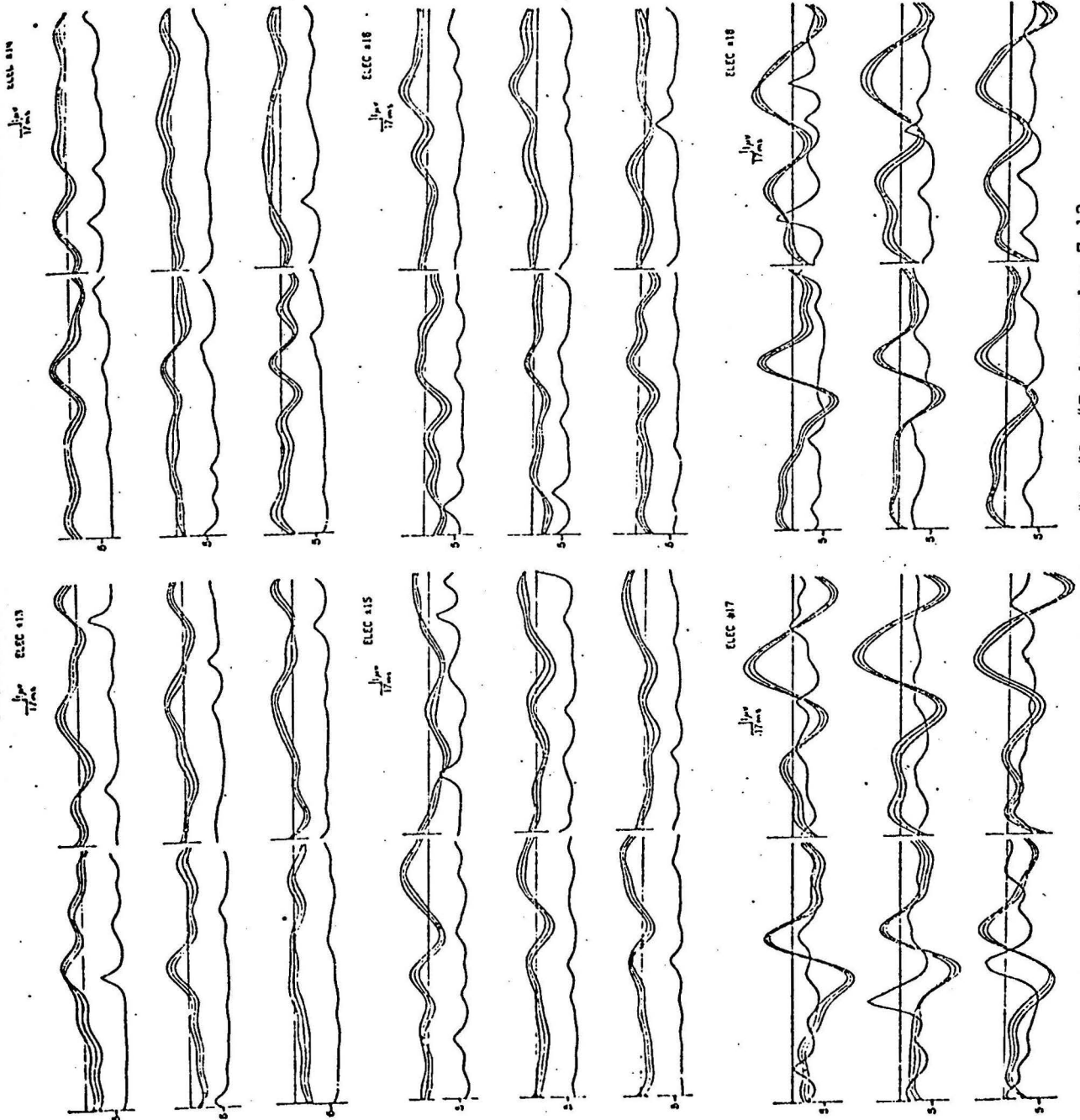


Fig. 3.9c MEP and S/N traces. Sub. 3 Tex. #1, #2, #7 electrodes 7-12

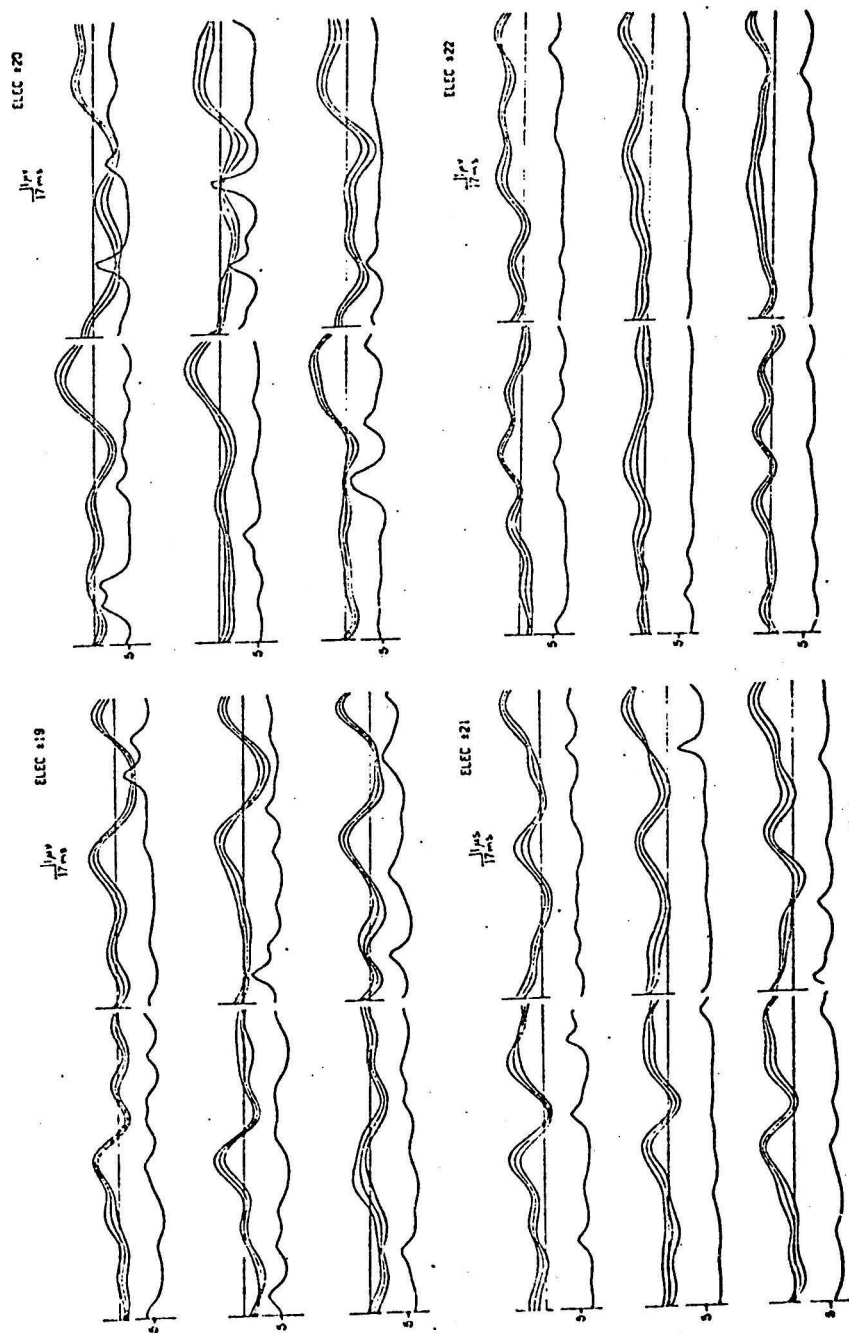


Fig. 3.9d MEP and S/N traces. Sub. 3 Tex. #1, #2, #7 electrodes 19-22

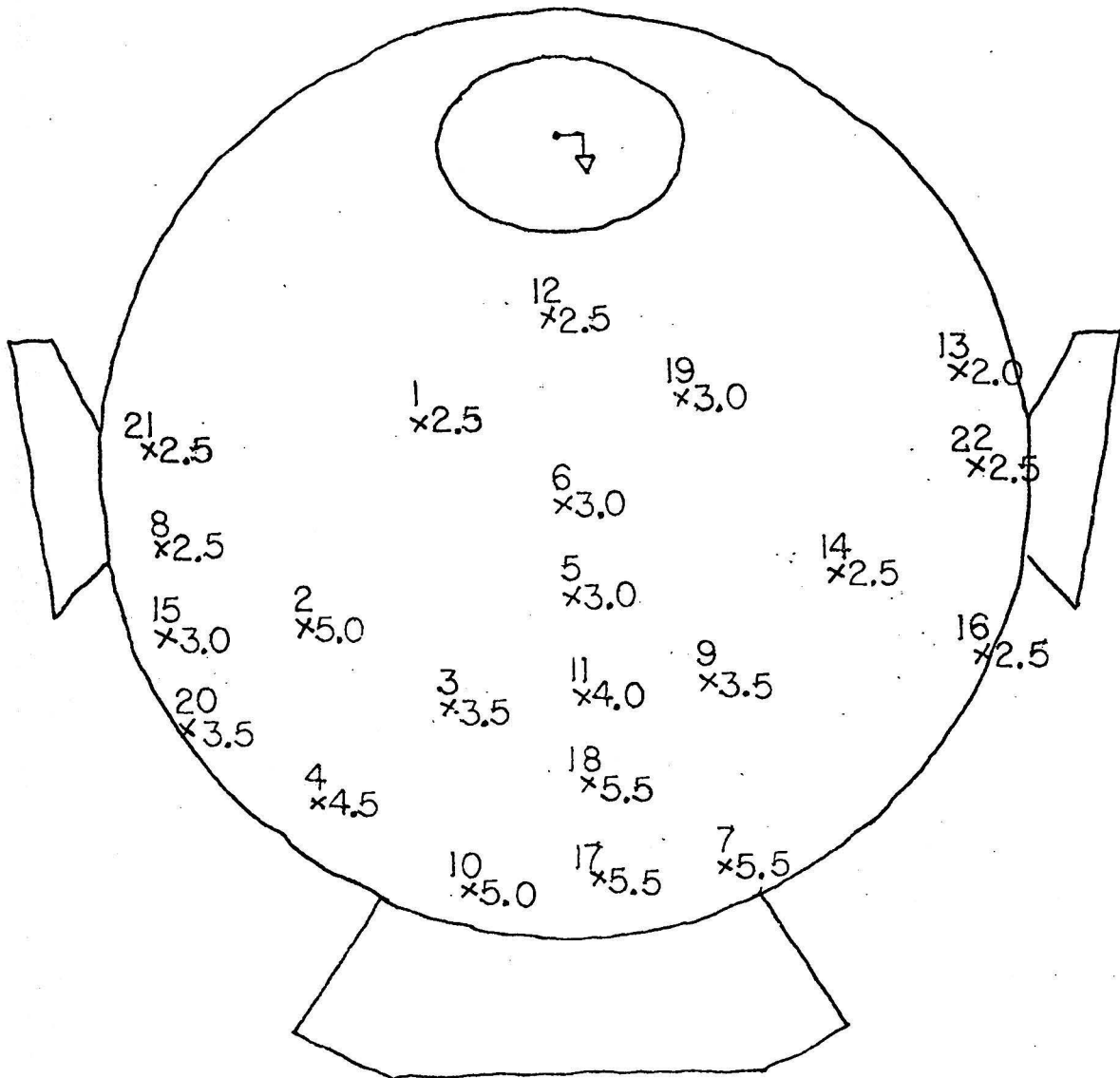


Fig. 3.10 Electrode locations and average S/N for sub. 3

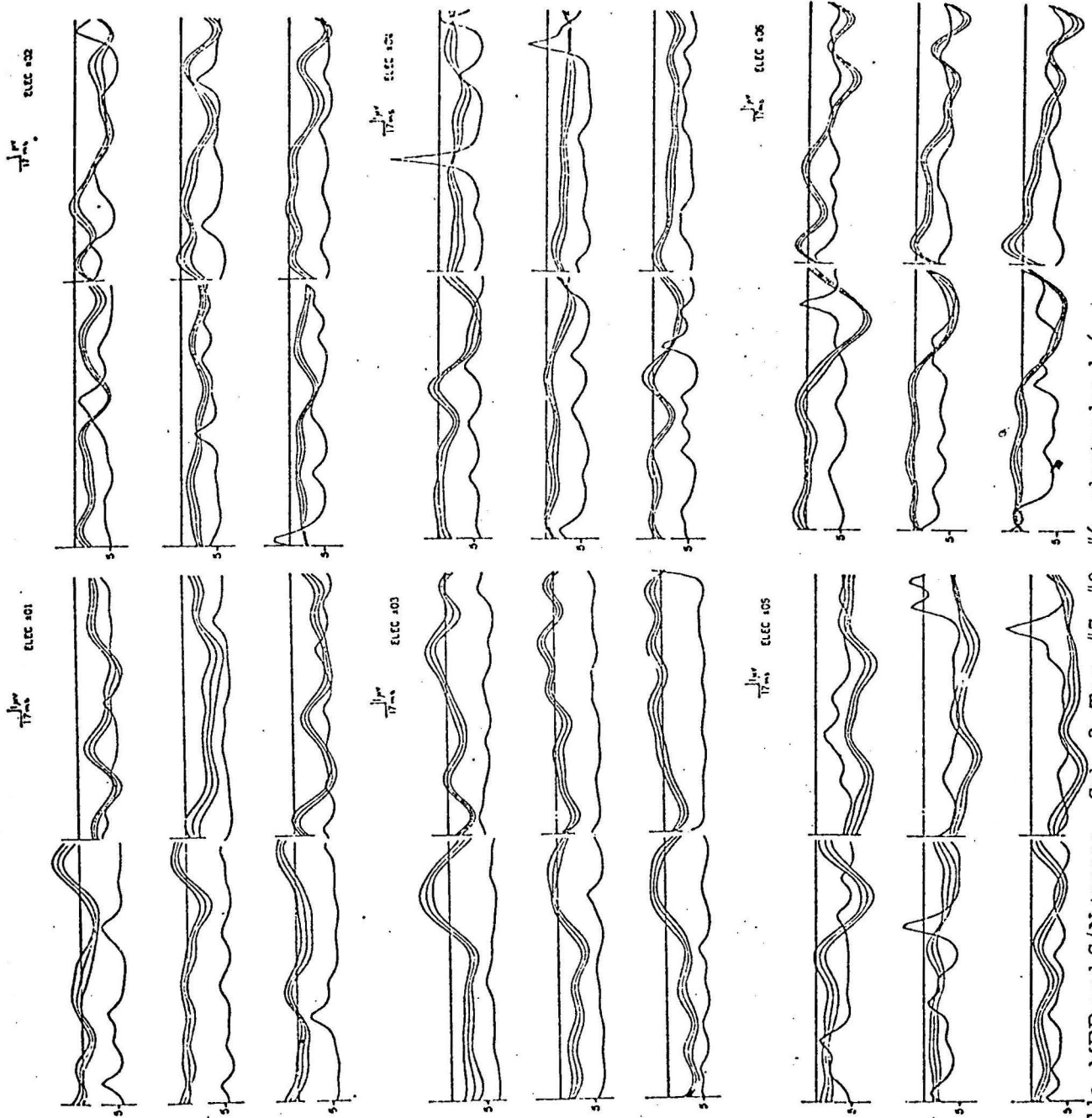


Fig. 3.11a MEP and S/N traces. Sub. 2 Tex. #7, #8, #6. electrodes 1-6

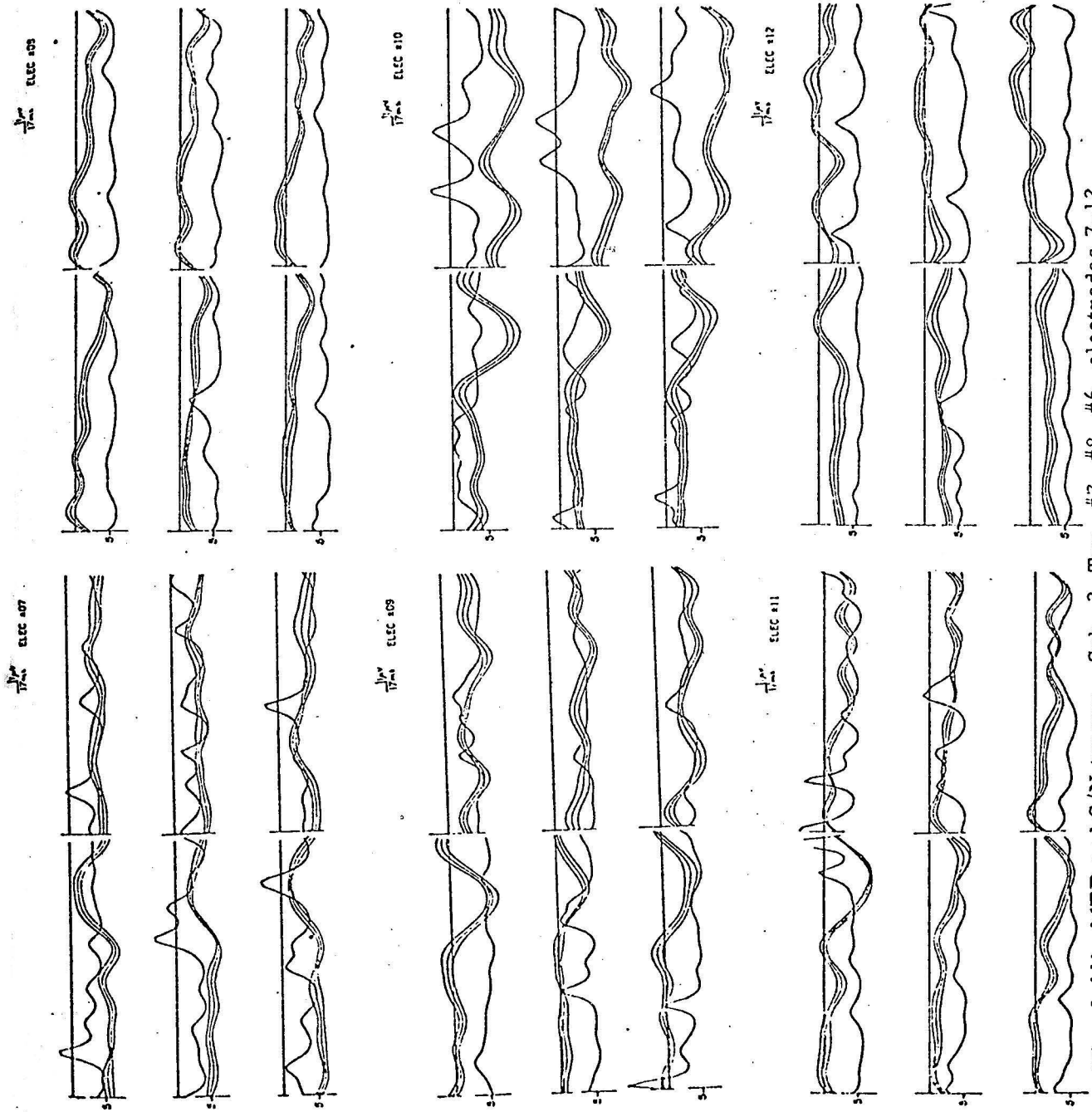


Fig. 3.11b MEP and S/N traces. Sub. 2 Tex. #7, #8, #6. electrodes 7-12

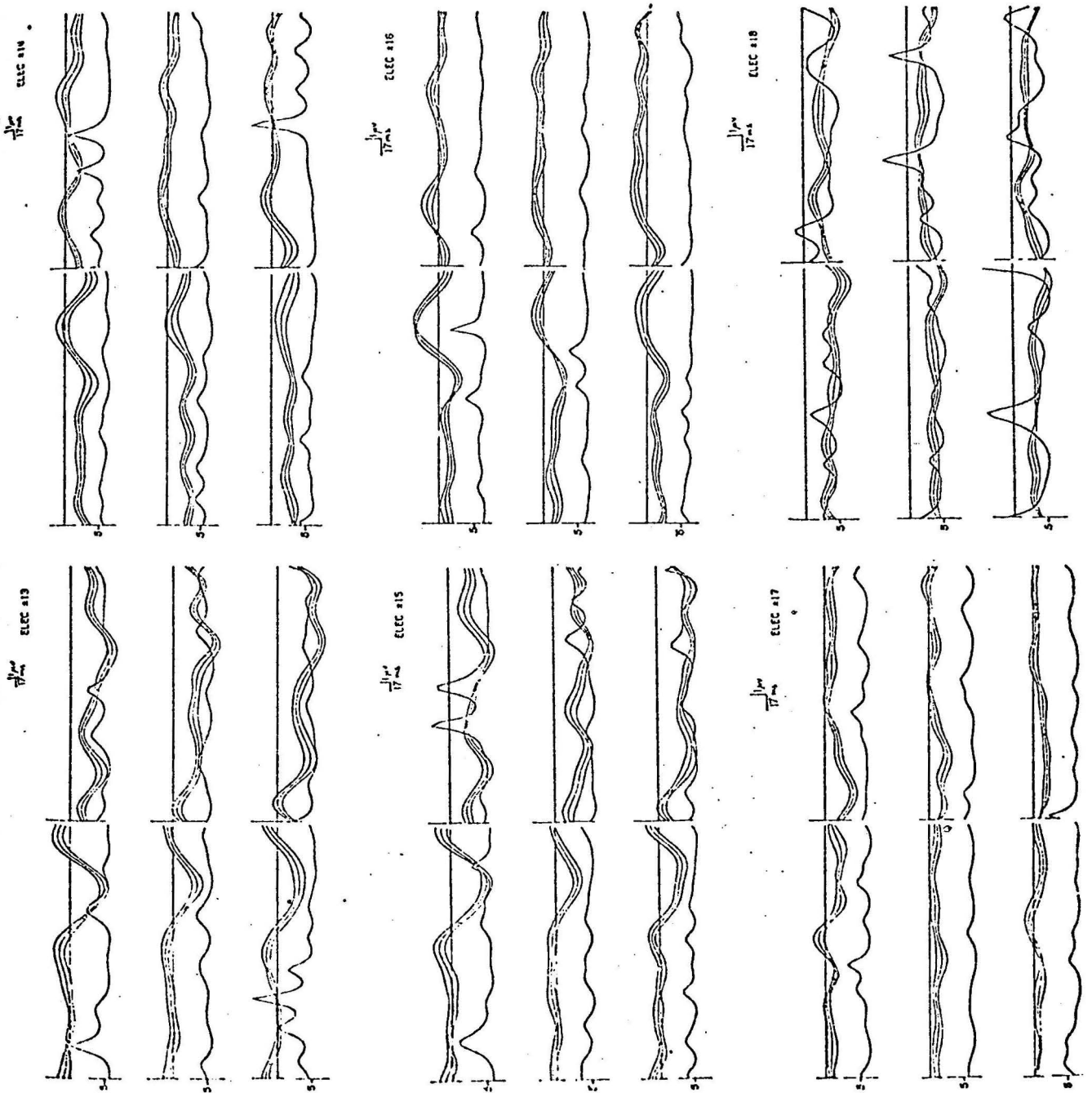


Fig. 3.11c MEP and S/N traces. Sub. 2 Tex. #7, #8, #6. electrodes 13-18

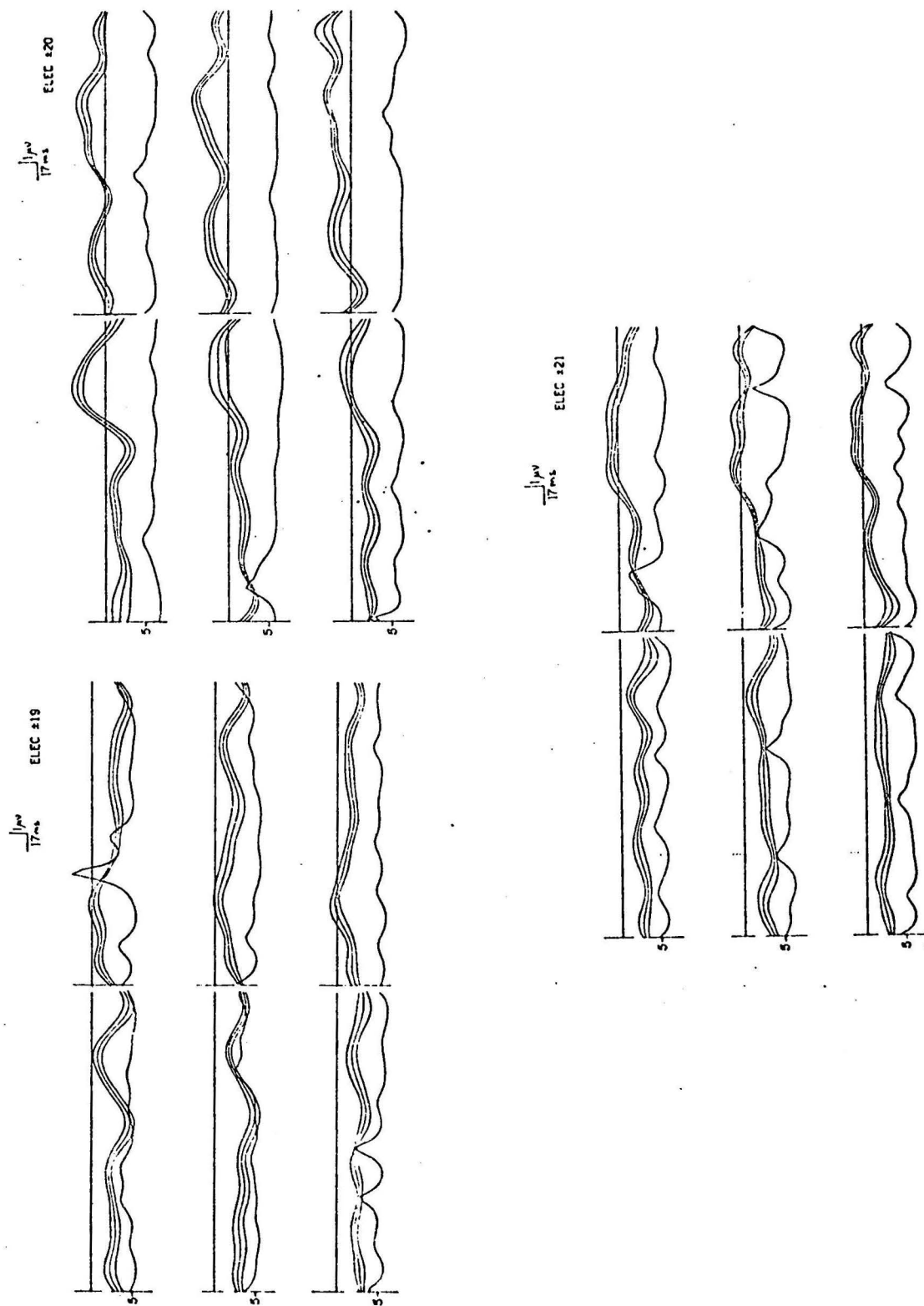


Fig. 3.11d MEP and S/N traces. Sub. 2 Tex. #7, #8, #6. electrodes 19-21

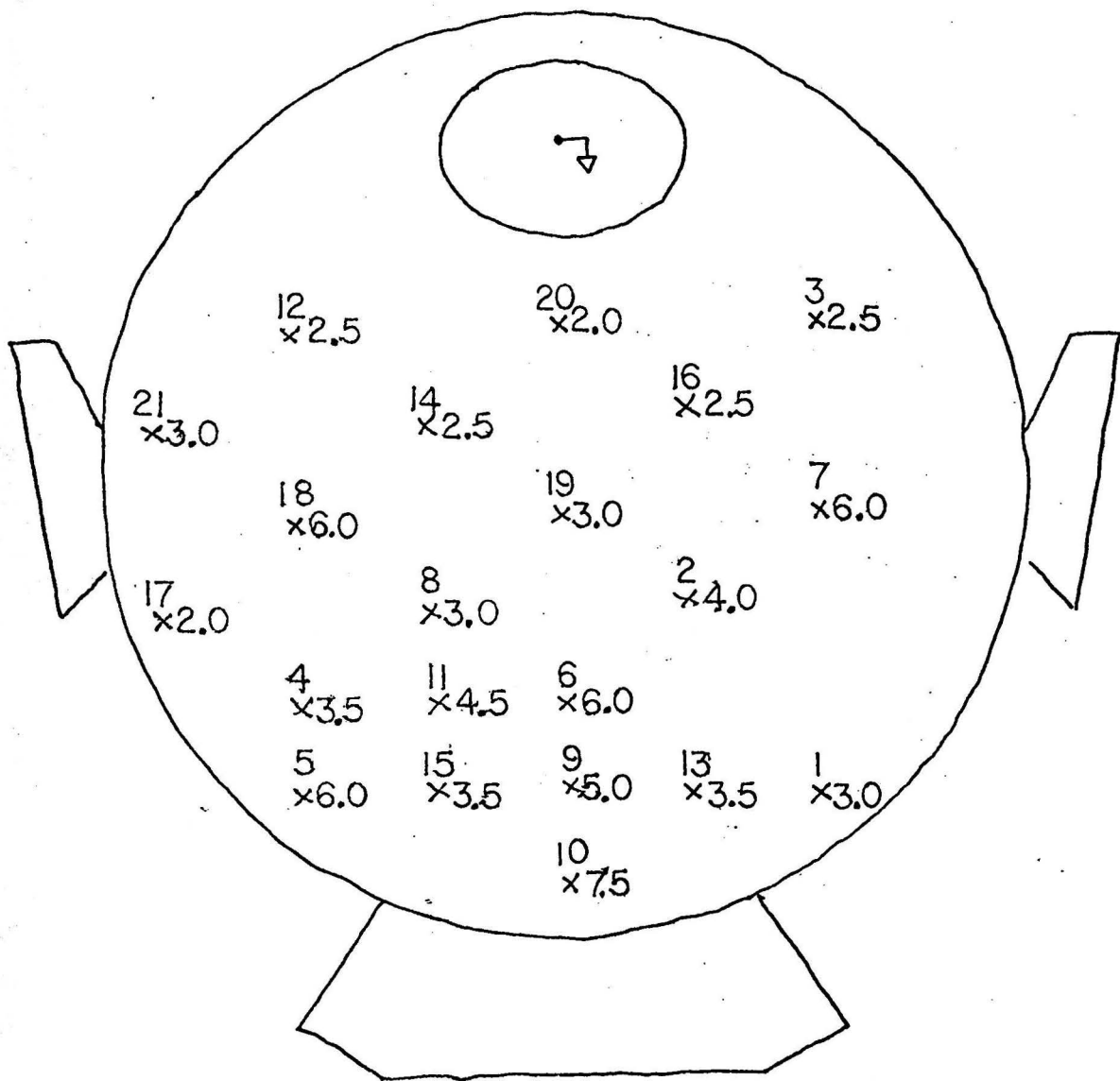


Fig. 3.12 Electrode locations and average S/N for sub. 2

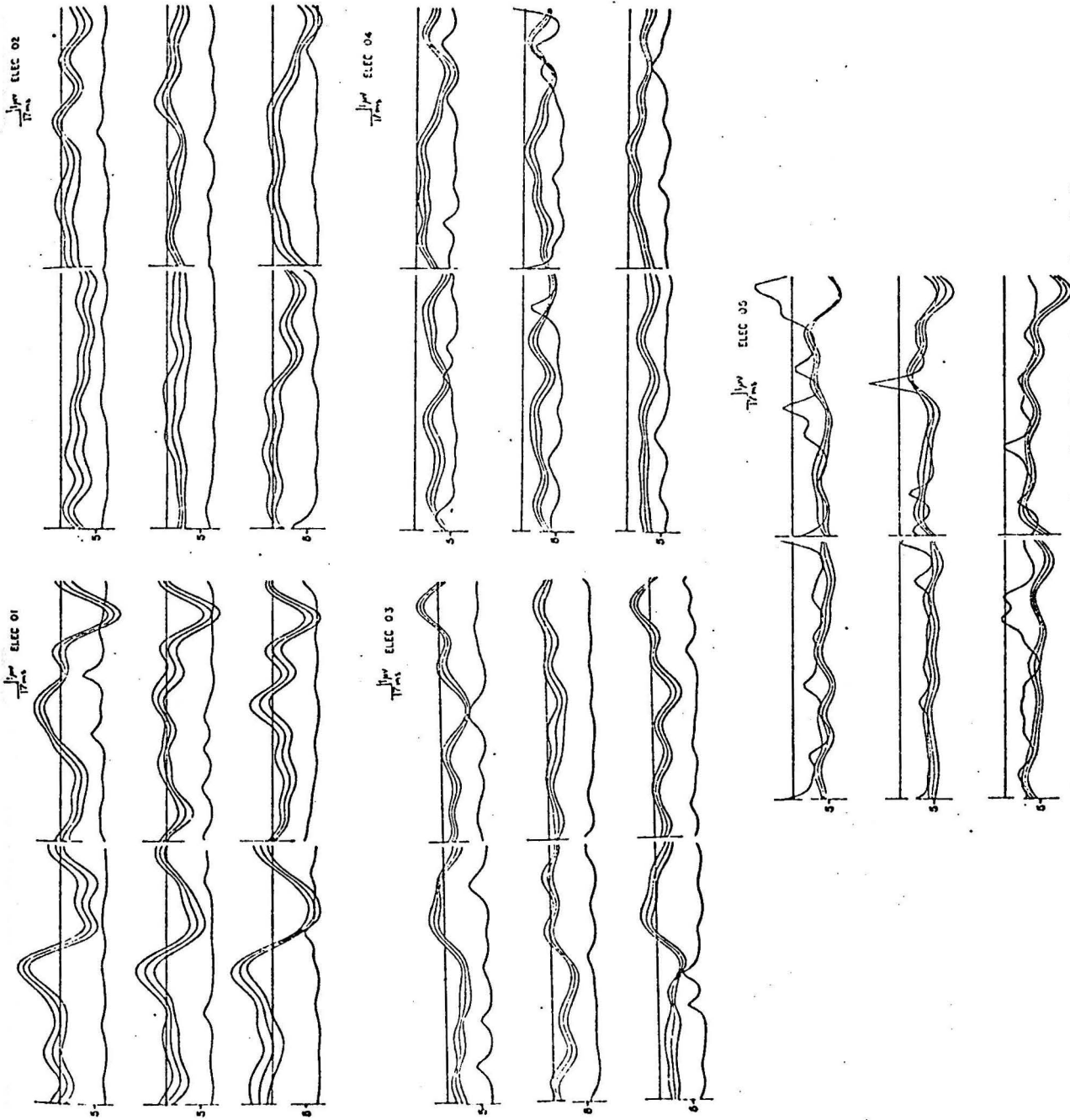


Fig. 3.13a MEP and S/N traces. Sub. 1 Tex. #4, #5, #13. electrodes 1-5.

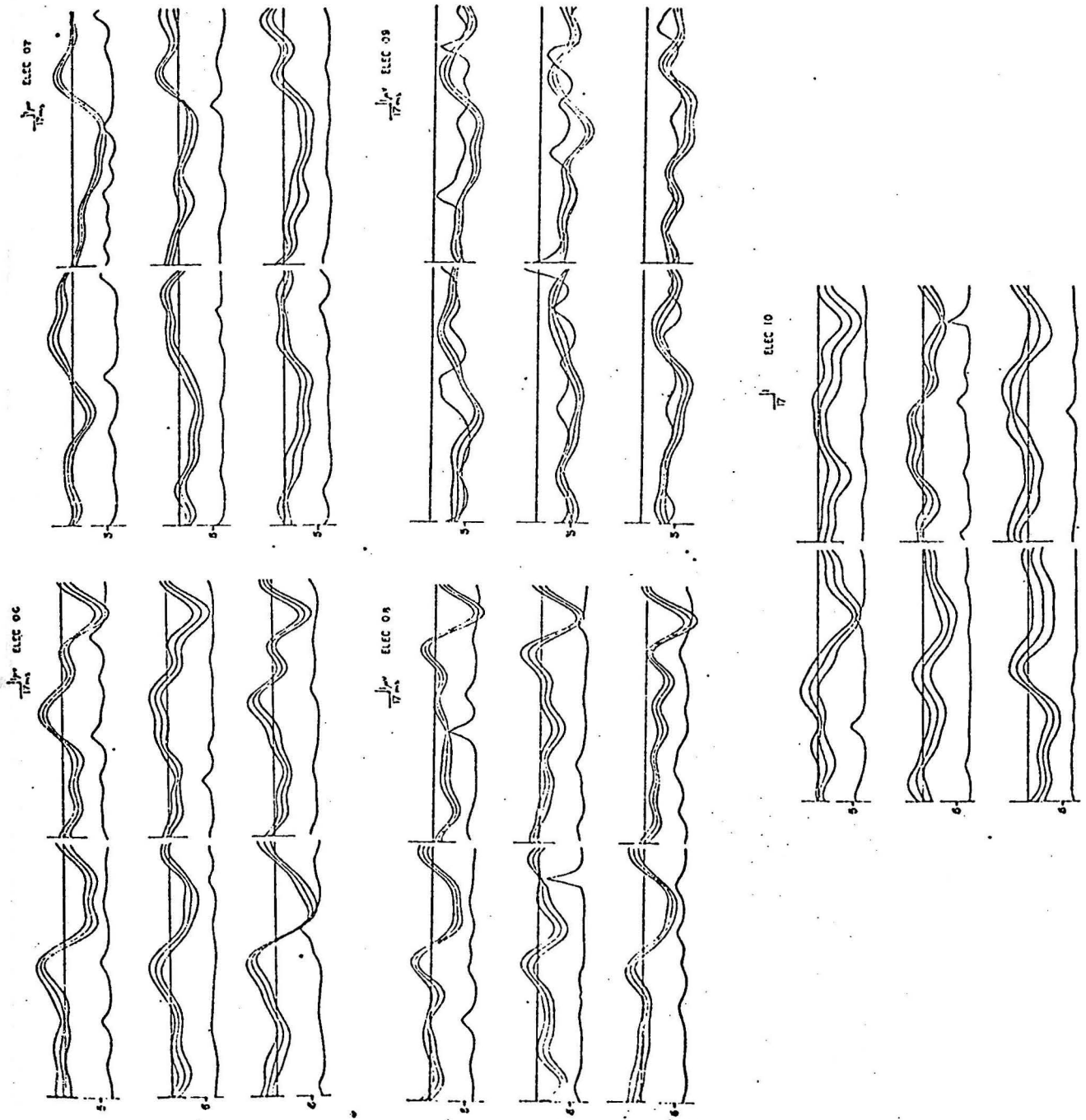


Fig. 3.13b MEP and S/N traces. Sub. 1 Tex. #4, #5, #13. electrodes 6-10

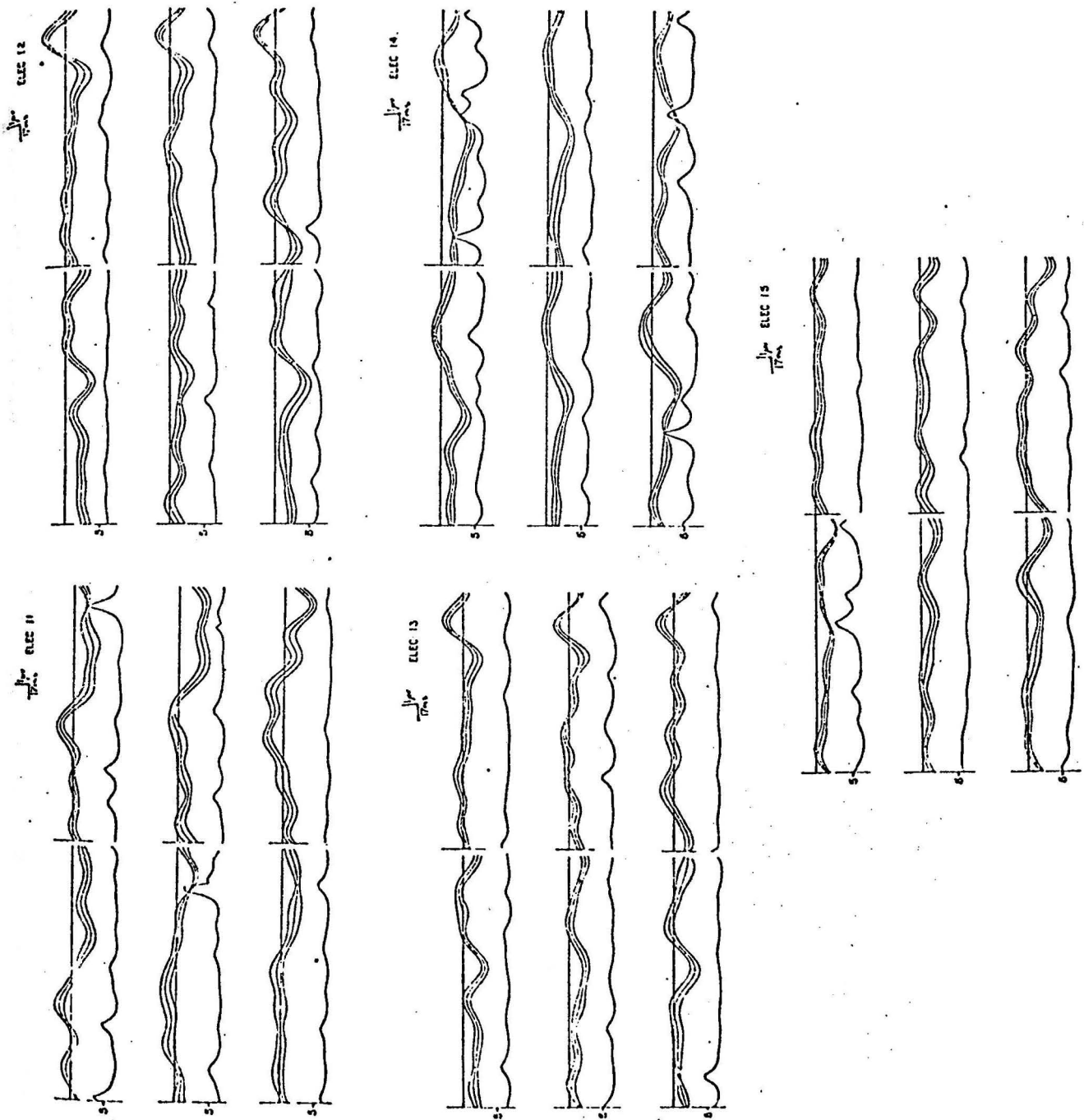


Fig. 3.13c MEP and S/N traces. Sub. 1 Tex. #4, #5, #13. electrodes 11-15.

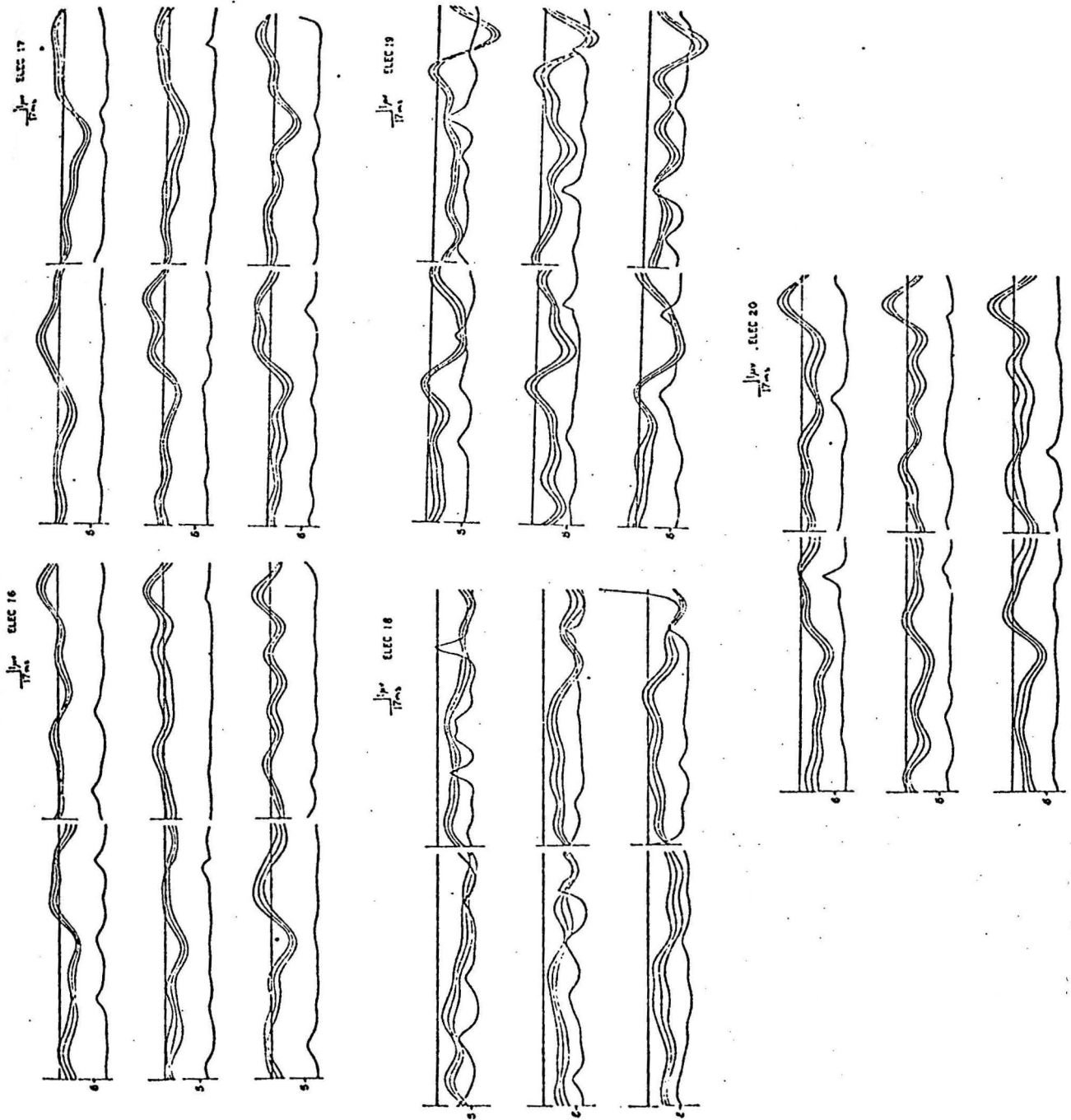


Fig. 3.13d MEP and S/N traces. Sub. 1 Tex. #4, #5, #13. electrodes 16-20.

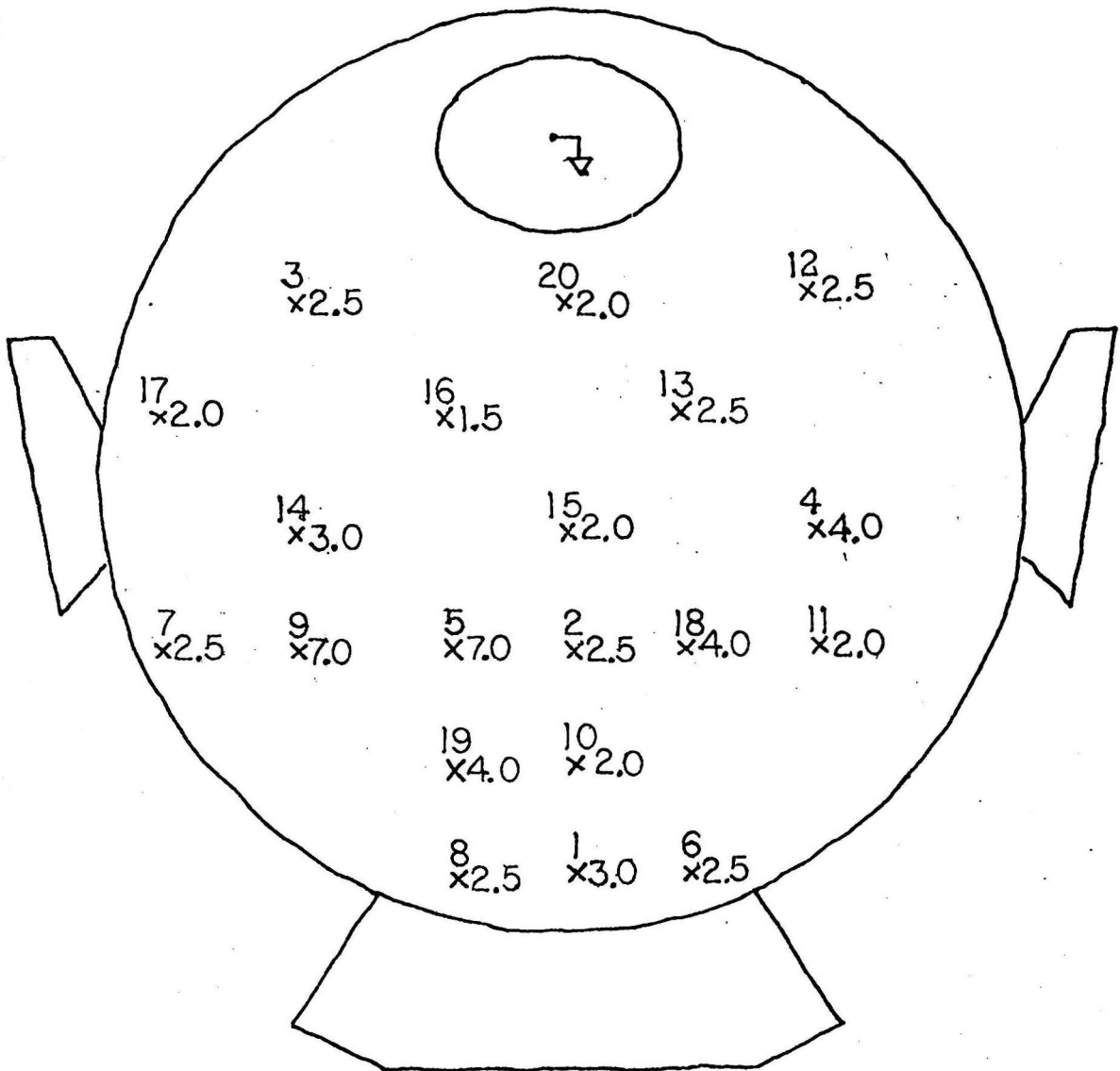


Fig. 3.14 Electrode locations and average S/N for sub. 1

the reversal response is well known and has been referred to as a rectifier-like effect by Spekreijse et al., (1973). The latencies of subject 2 and 1 responses to both appearance and reversal are longer than those of subject 3, and moreover, there is much more asymmetry in the appearance/reversal responses. The reversal response for both subject 1 and subject 2 is generally smaller on most electrodes than the appearance response.

Inspection of electrode MEP's for different stimuli on the same subject reveals few obvious differences. Perhaps in some cases, amplitude and latency variations are present, but the systematic consideration of such differences for all electrodes on each subject is a formidable task. The automation of this task in such a way to allow immediate, lucid inspection of the variations on all electrodes is the primary value of the source analysis, as will be shown in the next chapters.

IV. ANALYSIS AND DISPLAY TECHNIQUES

Two data sets have been presented in the previous chapter: one a group of matrices representing the discrimination of certain stimuli by test subjects; the other a series of scalp potentials recorded during the visual response to the same stimuli. The scalp potentials have been amplified, filtered and digitally recorded. Then median values for a large number of stimulus cycles were computed, digitally filtered and averaged as explained in Chapter III. The dissimilarity matrices were calculated from the fraction of correct answers out of the total exposures to each pair of textures based on the premise that 50% correct is chance level and corresponds to zero dissimilarity. We now present the techniques to be applied in the analysis of this data.

Scalp recordings represent the fluctuations in potential difference between separate locations on the head. In the past, practical considerations of recording and analysis capabilities precluded systematic study of the positional variations in the scalp potential distribution. Modern data collection and storage techniques can easily handle records from multiple electrode arrays. Since it has long been known that scalp potentials vary as a function of electrode location, new information may be learned by carefully studying this aspect of scalp electrode recordings. Hence, the evoked potentials obtained in this investigation are cast in the context of a spatio-temporal analysis.

Studies of contour maps of scalp potentials effectively encompass the complete information from multiple electrode records simultaneously. The investigator is able to comprehend not only the

activity at a single scalp location, but also how this activity is integrated into the entire electric field distribution. Such studies of the behavior of surface fields have led to the interpretation of scalp electrical phenomenon in terms of source localization theory. In this work, a source localization analysis has been applied to the study of pattern evoked potentials. The sources are simple electrical generators located within a model head such that the fields they produce on the surface of the model are a good approximation to the experimentally measured potentials on the subject. A major effort of this study has been to determine the relationship of the localized sources to the perceptual aspects of the VESP stimuli.

The psychophysical studies comprise an independent evaluation of the percepts generated by our group of random dot patterns, several of which were then used as VESP stimuli. The dissimilarity matrices representing the discriminability of the various possible pairs in the stimulus group are treated by a multi-dimensional non-metric scaling approach. This technique constructs a structural representation of the discriminability of objects within the test group. Each intersection point of a line structure is assigned to a test object. The object points are arranged by an iterative process so that interpoint distances are representative of the measured inter-object dissimilarities.

Non-metric Multi-dimensional Scaling

The object of "discriminability tests" is the identification of the criteria which are used to perform the discrimination. Then the study of processes which might operate according to such criteria is begun. Discrimination experiments such as the one presented in this thesis

have as raw data a set of essentially non-metric proximity measures.

The use of the term "proximity" for data which are strictly measures of discriminability or dissimilarity already implies the notion of physical nearness in some space. The proposition has been tendered (Shepard, 1962) that dissimilarity measures are interpretable as proximity relations within a spatial structure. It is thus necessary to define some transformation of the non-metric psychological "distance" into actual distances in some metric space in order to recover the spatial structure underlying the original data.

Torgerson (1958) has for example, proposed mapping the group of objects into a euclidean space. The critical factor in the proposed spatial mapping is the distance function which transforms the psychological measures into true distances.

Shepard (1962) proposed two conditions: 1) whatever the exact nature of the distance to dissimilarity function may be, its slope must be monotone ; 2) the optimum space for the structure is that of the minimum dimensionality for which 1) still holds.

Shepard has shown that the two requirements of monotonicity and minimum dimensionality are sufficient to uniquely identify a structural representation of proximity data.

Monotonicity requires that the rank order of the $N(N-1)/2$ distances among the N objects of the group should correspond directly to the rank order of the $N(N-1)/2$ dissimilarity measures. The requirement is that if object C was found to be more different from object A than was object B , the metric distance $A-C$ must be greater than distance $A-B$ by some acceptable degree of approximation. For

a group of N objects with any possible given rank order of $N(N-1)/2$ dissimilarities (including ties), a set of N points with inter-point distances of matching rank order can always be found in an $(N-1)$ - dimensional space. Each point is connected by $N-1$ distances to the other points in the structure, thus $N-1$ independent dimensions will always allow the freedom to adjust those distances to the desired rank order. Any number of suitable structures can be defined in $N-1$ space.

Shepard provided the insight that the addition of the minimum dimensionality requirement to the monotonicity condition guarantees the existence of a non-trivial and unique structure. This result is obtained from a consideration of the relation of dimensionality to the variance of inter-point distances. The variance of the distribution of distances in a hyperspherical region of t - dimensional space has been shown (Hammersley, 1950) to depend inversely on the number of dimensions, t . In $N-1$ space, the variance among distances separating N points can be minimized by placing the points on an N -th order simplex. As the space is flattened by eliminating dimensions, the variance of inter-point distances increases. Shepard concluded that an equilibrium structure could be reached by moving points in $(N-1)$ space along vectors which maximized inter-point distance variance while maintaining the desired rank ordering of those distances. A rotation of the final $(N-1)$ - dimensional structure to principal axes and elimination of the axes with negligible variance then yields the optimal configuration in a minimum dimensional space. Shepard's technique performed well on proximity data from metric structures subjected to random additive noise (Shepard, 1962) as judged by the metric deter-

minacy criteria introduced by Young (1970) (how well recovered distances correspond to original metric distances).

The contribution of Shepard is the incorporation of the rank ordering of measured non-metric proximities directly into the iterative scheme for construction of a metric structure. Previous studies dating from the original work of Coombs (1950) on psychological scaling without a unit of measure did not use a self-correcting approach. Generally, the early procedures consisted of a one-dimensional scaling of dissimilarities into metric distances followed by construction of a structure of points separated by approximately those distances. Independently of Shepard, Coombs (1958), Hays (1961), and others expanded the one-dimensional scheme to higher ordered spaces. Hays in particular also proposed the concept of somehow basing the construction of a metric structure on just the rank order of the given dissimilarity or proximity measures.

While Shepard considers the departure from monotonicity of the recovered structure, he gives it secondary importance as a criterion for deciding when the optimum structure has been reached for a given problem. Kruskal (1964a) makes the monotonicity condition the key to the scaling problem. Kruskal defines the problem of multi-dimensional scaling as one of statistical fitting akin to least-squares regression analysis. Some essentially non-metric quantities (similarities, dissimilarities, proximities) have been obtained and it is desired to find the metric configuration which best represents those conceptual quantities. Kruskal proposes that some statistic be defined which measures how well a configuration represents a set of dissimilarities

in terms of monotonicity. Once a "goodness of fit" statistic is defined, a regression algorithm can be designed to minimize that statistic for a given number of points in a given order space.

Given a configuration of points in an N -th order metric space, a monotone regression of distance upon dissimilarity is performed and the residual variance is taken as the quantitative measure of how well the inter-point distances in the metric space represent the given dissimilarities. The residual variance is suitably normalized and defined as the 'stress' between the metric structure and the non-metric quantities the structure attempts to represent. Using the scheme just defined, the definition of the optimum configuration in a given order space is straightforward: the configuration of minimum stress is the best possible representation for the given non-metric data.

The Kruskal method operates on only the rank ordering of a given number, $M=N(N-1)/2$, of dissimilarities obtained for a group of N objects. Somehow, a starting configuration in a space of order N is obtained. The choice of dimensionality, t , for the metric space depends on the nature of the particular experiment from which the data was obtained. In many experiments, it is desired to obtain an acceptable representation of the data in a space of minimum dimensionality. The Kruskal analysis may be performed sequentially in spaces of decreasing order and the behavior of the minimal stress as a function of dimension can be used to select the optimal space.

Some distance metric r is assumed in the starting space of the form:

$$d_{ij} = \left[\sum_{s=1}^t |x_{is} - x_{js}|^r \right]^{1/r} \quad (4.1)$$

where d_{ij} is the distance between points x_i and x_j which are located according to orthogonal coordinates $x_{i1}, x_{i2}, \dots, x_{it}$ and $x_{j1}, x_{j2}, \dots, x_{jt}$.

The non-metric dissimilarity measures, δ_{ij} , are rank ordered. Assuming for simplicity no ties exist in the dissimilarities, a strict ascending order is obtained: $\delta_{i_1 j_1} < \delta_{i_2 j_2} < \delta_{i_3 j_3} < \dots < \delta_{i_m j_m}$. The rank order is the only information actually used in the scaling analysis. Having obtained by some means a configuration of N labeled points in t -space, the analysis starts by quantitatively defining how well in the sense of Shepard's monotonicity hypothesis the configuration represents the dissimilarity data. A graph as employed by Kruskal (1964a) is useful for visualizing the procedure. Fig. 4.1 shows a plot of dissimilarity δ on distance d , taken from Kruskal (1964a) wherein such a plot is designated a 'scatter diagram'. Both axes are scaled in linear units representing the relative dissimilarity measures and the inter-point distances as computed from the point coordinates of the configuration according to some metric formula.

For the Shepard monotonicity condition to be fulfilled, it is required that when moving from a given point to any other point higher on the dissimilarity axis of the scatter diagram one must move in the direction of increasing distance. The stars in Fig. 4.1 represent the 10 distances and dissimilarities between 5 points in a starting configuration and 5 objects of a test group. The first step in the test for monotonicity is to fit a monotonically ascending curve to the stars of

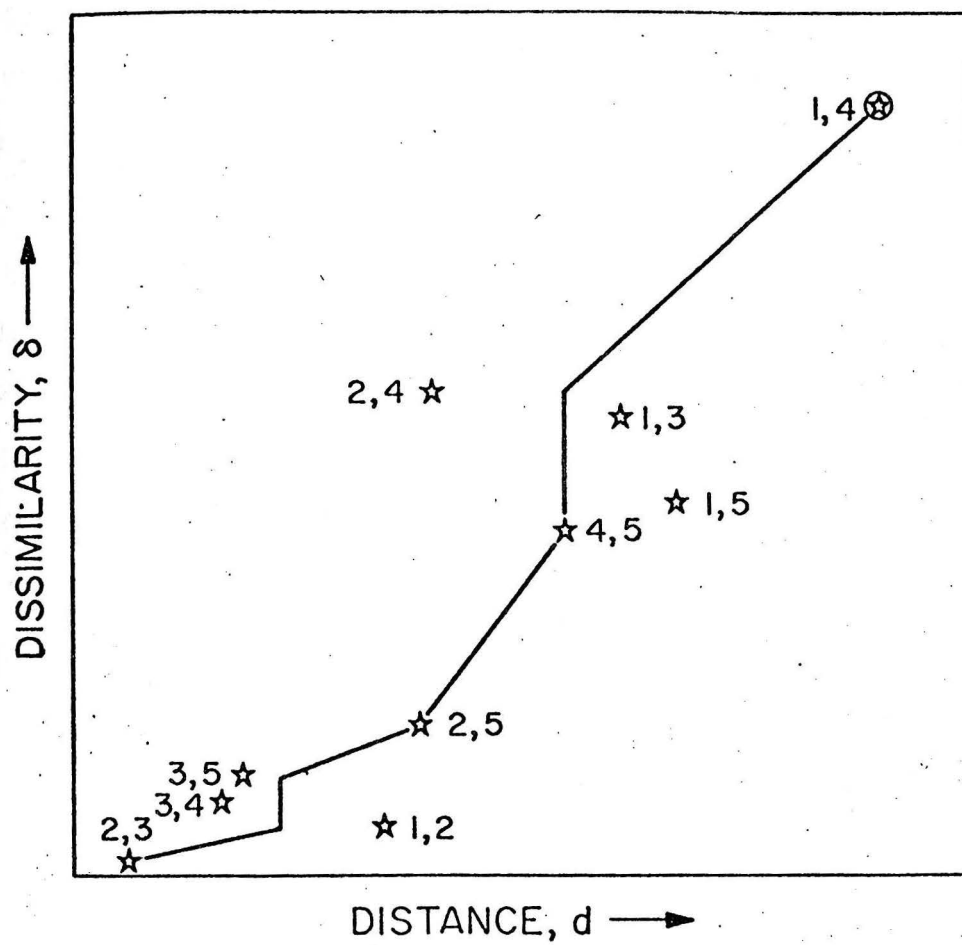


Fig. 4.1 Scatter diagram of dissimilarity vs distance from Kruskal (1964a).

the scatter diagram. Once the curve is obtained, the amount each star falls off the curve yields the desired quantitative measure of departure from monotonicity.

The amount of departure of a star from the regression curve depends on the direction taken from the star to the curve. Note that any direction other than parallel to the distance axis will require arithmetic manipulation of the relative dissimilarity positions of the stars. By measuring the differences of the monotone approximation points from the actual scatter diagram points only in the direction parallel to the distance axis, the relative dissimilarity measures are not combined or manipulated in any fashion. The relative sizes of the dissimilarities enter the calculations only in that they determine the shape of the monotone curve and hence, the amount by which a given star departs from the curve. Since the dissimilarities are not added or subtracted, Kruskal's technique, like Shepard's, is not guilty of any assumptions concerning the interactions of these non-metric quantities.

Fig. 4.2 shows a monotone curve of best fit to the 10 distance/dissimilarity stars. Using the restriction of operating only on metric distances, a raw measure of the departure of the actual star positions from monotonicity (the desired stress parameter) is obtained by the method of summing squares of the distance-coordinate deviations as below.

$$\text{Raw Stress} = \sum (d_{ij} - \hat{d}_{ij})^2 \quad (4.2)$$

where the numbers, $\hat{d}_{ij}$, are the distance axis coordinates of the points on the monotone curve which approximate the actual star posi-

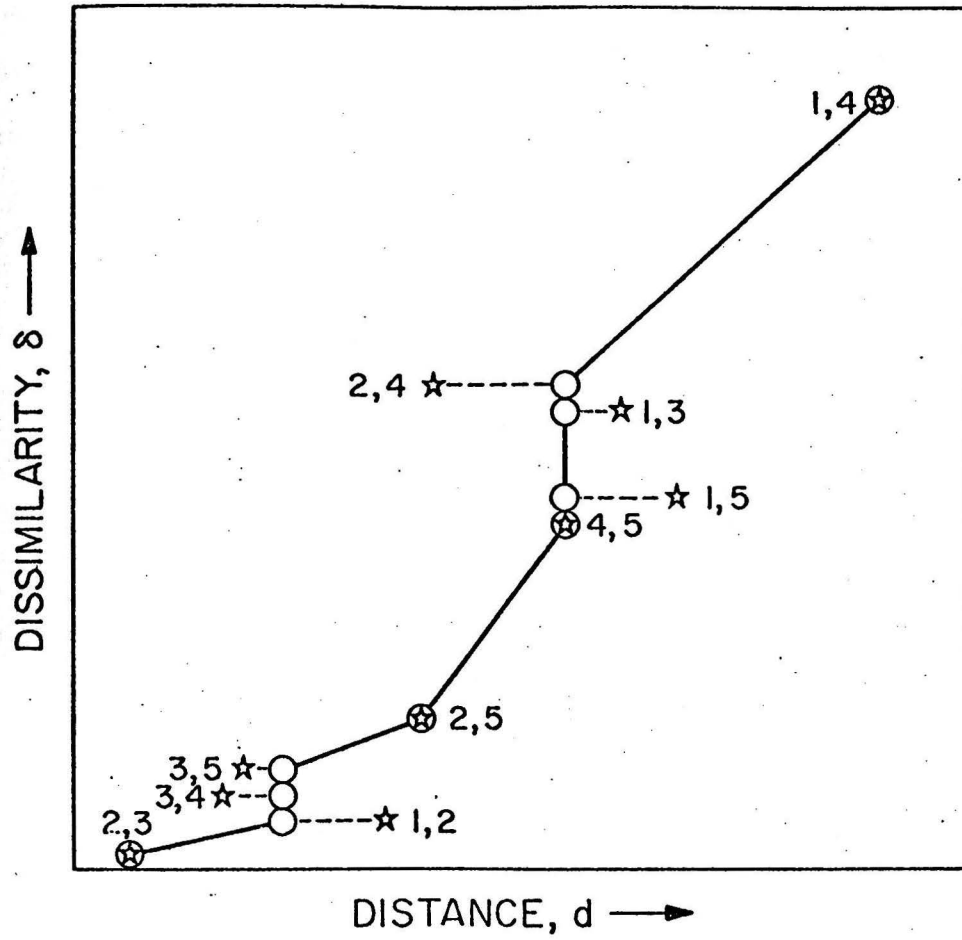


Fig. 4.2 Best fit monotone curve (circles) to dissimilarity/distance data of Fig. 4.1 (stars) from Kruskal (1964a).

tions. The $\hat{d}_{ij}$ are obtained by requiring that the raw stress be a minimum subject to the condition of monotonicity; that is:

$$\hat{d}_{i_1j_1} \leq \hat{d}_{i_2j_2} \leq \hat{d}_{i_3j_3} \leq \dots \hat{d}_{i_mj_m} \quad (4.3)$$

Normalizing the raw stress by the sum of squares of the actual configuration distances makes it invariant under changes of scale of the configuration (i.e. uniform stretching or shrinking). Thus, Kruskal defines the optimization parameter which measures the goodness of fit of a given configuration to a set of non-metric data subject to the monotonicity condition:

$$\text{stress} = S = \left[\frac{\sum_{i \langle j} (d_{ij} - \hat{d}_{ij})^2}{\sum_{i \langle j} d_{ij}^2} \right]^{1/2} \quad (4.4)$$

Having defined stress, the configuration in a given space which is by definition the best representation for the given non-metric dissimilarity data is the one for which S is a minimum over all the possible configurations which can be constructed. It is supposed that the measured dissimilarities are statistical approximations to some "true" quantities which have their basis in physical reality and can be perfectly represented by some "true" configuration in a space of suitable metric, r , and suitable dimensionality, t . When the "best-fit" configuration is found, it is assumed that the residual stress for it represents the amount of random error introduced by the method used to obtain the dissimilarity measures. The problem of obtaining the best fit configuration for a space of set dimensionality and metric is that of the minimization of a function of several variables. The stress

for a given configuration is a function of the $N \times t$ point coordinates as seen from the formulas for stress (4.4) and inter-point distances (4.1).

A computer algorithm developed by Kruskal at Bell Laboratories called KYST (Kruskal, 1973) was employed in this research to obtain structural representations of the data from perceptual experiments. The general procedure for computation is shown in block diagram form in Fig. 4.3. The technique is as follows. A starting configuration is either created or supplied by the user; it is normalized and inter-point distances are calculated. The best-fit monotonic series, $\hat{d}_{ij}$, are then obtained using the dissimilarity measures. Stress is calculated and the direction of steepest descent in the space of the $N \times t$ independent variables of the stress formula is determined. The iterative procedure can terminate if the gradient in the direction of steepest descent for S indicates a minimum has been obtained. If a further iteration is indicated, the present configuration is altered in the direction of steepest descent for S by some suitable step-size, α , and the process repeats.

The scaling program of Kruskal effects the application of Shepard's hypothesis to the perceptual data of this experiment with a minimum of assumptions and manipulations. The scaled structural representation of the dissimilarity data allows straightforward display and visualization of the perceptual relationships among objects in our test stimulus group.

Source Localization Analysis

The topographical distribution of scalp potentials for our exper-

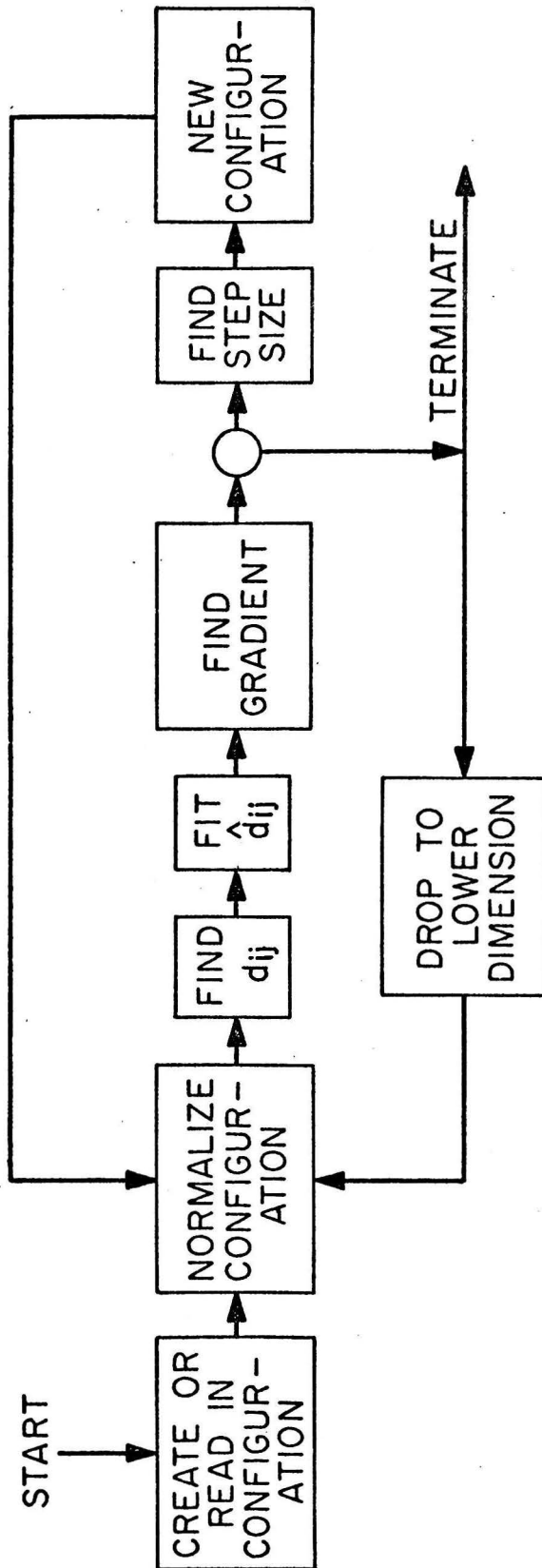


Fig. 4.3 Block diagram for multi-dimensional scaling algorithm from Kruskal (1964b).

iments is effectively described by the construction of contour maps of the electrode data from Chapter III. A typical equipotential map is shown in Fig. 4.4. Ears and a neck are appended to the circular projection of the head as viewer orienting clues. The ellipse within the field is the projection of a circle centered on the vertex of the subject's head thus providing a feel for the line of sight along which the head is viewed. Each contour line is labeled according to a scale from A to J in which A is the most negative potential and J is the most positive with neutral at approximately F or G. The maps are constructed according to the technique of Kavanagh (1972) using a contour plotting algorithm. A number of workers have currently adopted the fields display approach in clinical problems, among them Lehmann (1971, 1972), Henderson (1975), Bourne et al., (1971), and Estrin and Uzgalis (1969).

The concept of representing the fields measured on the scalp by discrete electrical sources is suggested by the mapping technique. Statistical analysis of simultaneous records from electrodes at various scalp positions (Barlow, 1959; Donchin, 1966; van Hoek, 1974) have shown the existence of significant interdependence suggesting that a single independent process underlies the response.

A thorough study of the dimensionality of the flash evoked potential can be found in Kavanagh, Darcey, and Fender (1976). The procedures are covered by various texts on the subject such as Cooley (1962) or Harmann(1961). Kavanagh et al., apply a factor analytic approach to the $N \times T$ matrix, V , of averaged data points obtained from sampling N electrodes at T sample instants. The

SUBJECT : TAD
STIMULUS : TEX ± 13
TIME : 152 MS AFTER REVERSAL

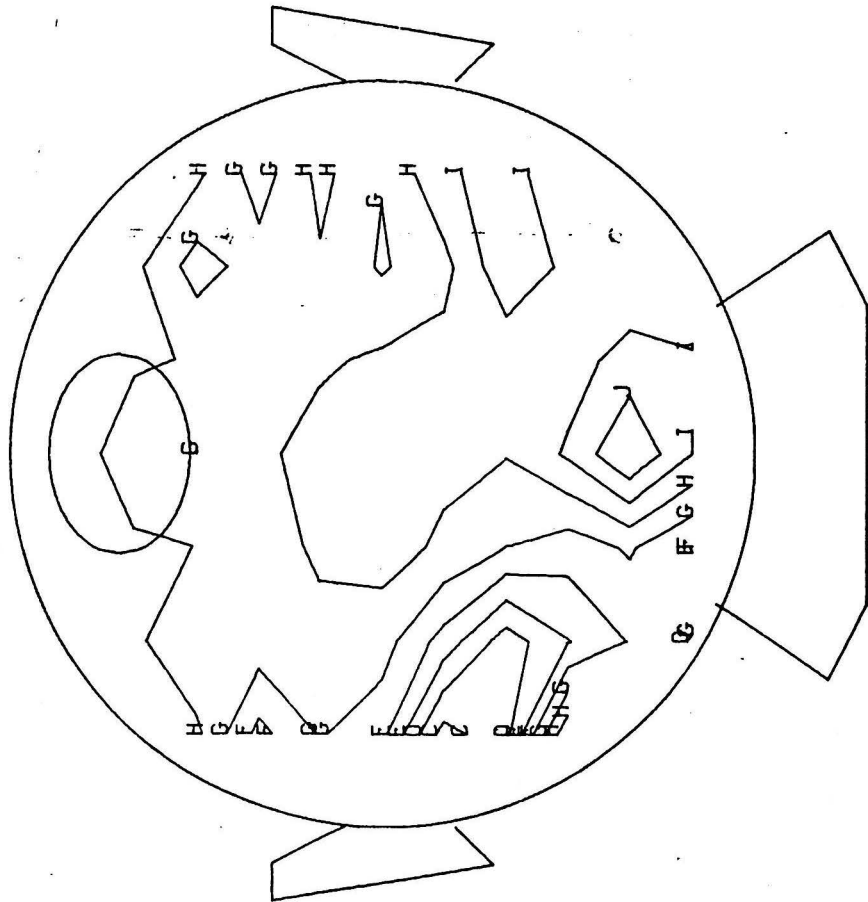


Fig. 4.4 Display format for equipotential scalp contour maps

analysis consists of solving for the eigenvectors of the variance-covariance matrix, VV^t . Then one determines how many of the eigenvectors are actually needed to account for the significant variance in the matrix. A criterion for the analysis of variance is the underlying rms noise of the data. Any variance in the data set that is equal to or less than the random fluctuations due to the inherent noise of the experiment cannot be allowed significance. Thus, only the eigenvectors that account for all the variance greater than the system noise are needed to describe the underlying independent operators in a given experiment.

Kavanagh found that all the significant variance for the flash evoked data of records from 47 electrodes could be accounted for by six independent eigenvectors, in fact, roughly 80% could be accounted for by only three eigenvectors. While such results do not specifically prove the hypothesis of discrete sources, they do prove that the signals on widely separated electrodes are driven by processes with only a small number of degrees of freedom. The finding of the interdependence of activity at numerous scalp locations points to two possibilities for the underlying process: either the cortical cells beneath each electrode site are fired neuronally from a common activation site such as thalamus, or the signals reaching the various electrodes arrive via passive electrical conduction through the neuronal tissues from a discrete active site.

One of the earliest investigators to propose a specific source model of EEG activity is Brazier (1949), who compared certain pathological EEG signals to the fields of an electrical current dipole in a sphere of homogenous conductivity. Others who have qualitatively

noted the apparent similarity of dipole fields to certain evoked scalp potential distributions include Fourment (1965), Vaughn and Ritter (1969), and Shaw and Roth (1955). Schneider and Gerin (1970) quantitatively located equivalent dipole sources for scalp potentials.

The rationale for choosing a dipole current source distribution as opposed to a monopole or some higher order parameterization stems from the following considerations. The factor analysis of the interdependence of multiple electrode records indicates the processes underlying the scalp activity are only marginally described by three independent components and really require more degrees of freedom for a satisfactory model. Also, the appearance of the scalp fields themselves is closer to a dipole distribution than a monopole but certainly not complex enough to justify higher order models. The work of Plonsey (1969) has shown that action potentials propagating along a single nerve axon create a pair of oppositely directed current sources; i.e. a dipole current source.

Thus, a superposition argument can be made for describing the activity of large groups of proximate neurons by a single dipole. The individual current sources could be oriented in such a way to completely cancel each other out producing no net field activity when viewed from the scalp. Conversely, if many cells are firing synchronously in the same direction, the net dipole moment will be large and similarly directed. The monopolar argument amounts to limiting the activity in the data set to three degrees of freedom. Thus, a monopolar hypothesis is more conservative than a dipole model in that it accepts only 75% -80% of the total variance in the data as being of

significance. In our analysis we have used the dipole model equations developed by Kavanagh (1972) although for the most part we have dealt with only the location parameters of the source solutions. A complete derivation of the dipole equations and associated programming techniques utilized in this research is presented in the Kavanagh thesis, Chapter IV and Appendices A and B. A general description of the problem is given here.

The source model is a set of parametric equations which attempt to reproduce the experimental data. The optimum model parameters are defined as those which result in the output of the model optimally fitting the output of the experiment in a least squares sense; i. e. root of sum of squared error between predicted and measured data points reaches a minimum. Kavanagh employs the algorithm of Marguardt (1963) to perform the minimization. The implementation of the nonlinear least squares algorithm generates confidence intervals for the optimal values of the model parameters. The confidence intervals are the limits within which there is a given probability of always finding the optimizing value for each model parameter. The interval size indicates the steepness of the slope of the minimizing function in the region of the minimum. Hence, if the confidence intervals are very small, there exists a unique set of model parameters which match the given experimental data. Alternatively, if the intervals are large, any of a wide range of model parameters can fit the data equally well. In our analysis we use the 95% confidence regions of the model parameters as an overall criterion to evaluate our solutions.

Kavanagh proposes two possible models for the environment surrounding the source dipole. The first approximation for the geometry and electrical characteristics of the head is a sphere of some homogeneous conductivity. In a homogeneous model the field of a current dipole can be described analytically by an equation of the form:

$$V(R, \theta, \phi) = \frac{1}{4\pi\sigma R^2} \left[V_1 V_2 + V_3 V_4 \right] \quad (4.4)$$

where R is the radius of the sphere, θ and ϕ are angular coordinates of any point on the surface, σ is the homogeneous conductivity, and V_1, V_2, V_3, V_4 are functions of the strength and location parameters of the source (x, y, z, P_x, P_y, P_z).

Of course, the head is composed of inhomogeneous conductive media. The brain is bathed in a high conductivity electrolyte, cerebrospinal fluid, it is wrapped in a tough membrane of reasonably high dielectric constant, then encased in bone and scalp. The effects of abrupt conductivity discontinuities on the propagation of electrical currents have been well studied and described. The problem in modeling the conductivity discontinuities in the human head is one of obtaining reasonable approximations for the significant media. Within the brain itself, relatively large conductivity differences exist between various regions such as the ventricles, the highly myelinated fibers of the mid-brain, and the cell-rich cortex. At the level of the scalp, these differences are dwarfed by the very large conductivity change from brain to bone tissue. High conductivity media are effective at dispersing a potential distribution incident upon them. Hence, current flowing from a localized region in cortex is initially dispersed by the

cerebro-spinal fluid (CSF), passes without much distortion (but high attenuation) through the lower conductivity skull, and then is dispersed through the scalp.

For the purpose of studying the effects of a discontinuous media on current flow and the resulting potential distributions, Kavanagh proposed the addition of radial discontinuities to the homogeneous conducting sphere model. Three concentric regions were introduced representing the brain and CSF, the skull, and the scalp, each of suitable radial thickness. Hence, in the second model, the brain is considered a homogeneous sphere encased in a shell of bone followed by a thin layer of scalp.

The studies by Kavanagh show the major difference in predicting source locations with the two models is that the homogeneous sphere model will locate a source at a greater depth than the shell model. This is because the effect of the conductivity changes at the various boundaries of the shell model causes greater dispersion of the current flow paths than occurs in an isotropic media. A convergent series of Legendre polynomials are involved in the field equations for the 'shell' model. Thus, the computation of potentials for the surface of the shell model is more time consuming than for the homogeneous model.

The geometric differences between a sphere and a human head can also be modeled. The head is approximated by an ellipse and then electrode positions are mapped from the ellipse onto a sphere. Hence, the concentric shell model can be quite a good approximation for the geometrical and passive electrical properties of the

head. Nevertheless, the goodness of the model does not guarantee the existence of discrete neuronal sources.

In this thesis, the physiological and anatomical aspects of source localization are only briefly touched upon. Rather, the source model is utilized as a concise characterization of the measured data and a particularly lucid visualization technique.

V. ANALYSIS OF RESULTS

Having collected both perceptual and electrophysiological data on the response of several subjects to the stimulus group of texture patterns, the analysis techniques described in the previous chapter are now used to reduce the data set to a manageable number of results. The scaling and dimensionality analysis techniques are used to obtain a metric representation of the discriminability among members of the stimulus group. Field mapping and source localization models are applied to the evoked potential records from multi-electrode arrays to obtain concise characterizations of the response for several textures.

The two experiments now analyzed contain various procedural and conceptual differences and hence are treated as separate and independent entities. Each experiment can stand on its own as a fundamental study in its particular field. The definition of qualitative perceptual aspects of texture in terms of statistical parameters and the application of scaling analysis to sort out the relations among those parameters casts our thinking on texture perception in a solid quantitative foundation. The systematic study of the spatial distribution of the VESP as a function of the statistical variations in dot patterns is a basic experiment which has not been performed previously because of the large investment of time and technology it involves. Hopefully, the results of the present study on scalp potential distributions will provide an impetus for other to utilize this rather painstaking but fruitful approach. Hence, in this chapter, perceptual and electrophysiological data are analyzed separately; the basic results

of the two studies will be discussed together and compared in the final chapter.

Multidimensional Scaling

The confusion matrices obtained from spontaneous texture discrimination tests were scaled onto metric structures in euclidian space of dimensionality 6 through 1. The Bell Laboratories (1973) program, KYST, described in Chapter IV, was used to generate the structures and evaluate their 'goodness of fit' to a monotone hypothesis. As shown in Chapter IV, the program KYST calculates a parameter called 'stress' as a measure of how well a particular structure represents the perceptual dissimilarity measures in the experimental data. The program minimizes the 'stress' between the perceptual dissimilarities and the structural interpoint distances in a space of given dimensionality. Ideally, for geometric structures perturbed randomly, the stress's curves show a discontinuity at the dimensionality of the particular structure. The stress in spaces of dimension higher than a given structure is quite low while in lower dimension spaces, the stress is large. Work has been done using actual perceptual data, geometrical structures, and randomly generated data to obtain insight on what a computed stress value means in terms of how well metric information is recovered from the data. Estimates for goodness of fit under the monotonicity requirement are given in Kruskal (1964a) as below:

<u>Stress</u>	<u>Goodness of Fit</u>
.20	poor
.10	fair

.05	good
.025	excellent

Curves of calculated stress versus dimensionality are shown in Fig. 5.1 for the three dissimilarity matrices of Chapter III. Slopes of the stress/dimension curves are also shown in Fig. 5.1. The curves show that for each subject both 3 and 4 dimensional structures are within the region of fair to good fit to the perceptual data. The 3-space configurations are on the boundary between fair to good while the 4-space structures are clearly acceptable. The first derivative curves show the slope is fairly flat in the 4D $\rightarrow$ 2D region and then rises sharply for the 2D $\rightarrow$ 1D region. Based on the stress/dimension results, a 3-dimensional representation is clearly the minimum required for the data set while a 4th dimension may be useful in some cases. The 3-dimensional structures for each subject are shown in Fig. 5.2. Study of the metric structures for each subject combined with a knowledge of the physical characteristics of each member in the stimulus group should yield an insight on the nature of the perceptual processes involved in the texture discrimination task. Comparison of structures among subjects should also contribute to the interpretation of the data by revealing what aspects of the structures are common to all subjects and what aspects represent the peculiarities of each individual.

Comparison of Structures

One tool used in studying the metric structures derived from psychophysical experiments is to identify the directions in the structure space along which either the maximum possible interpoint vari-

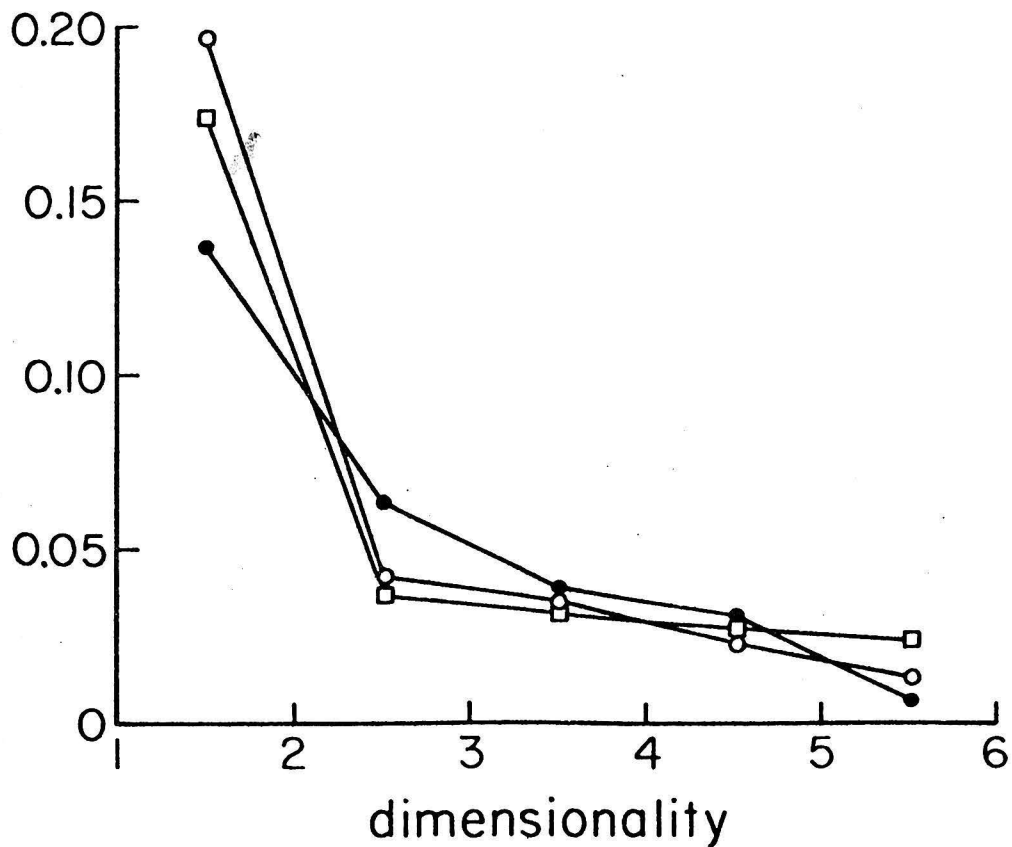
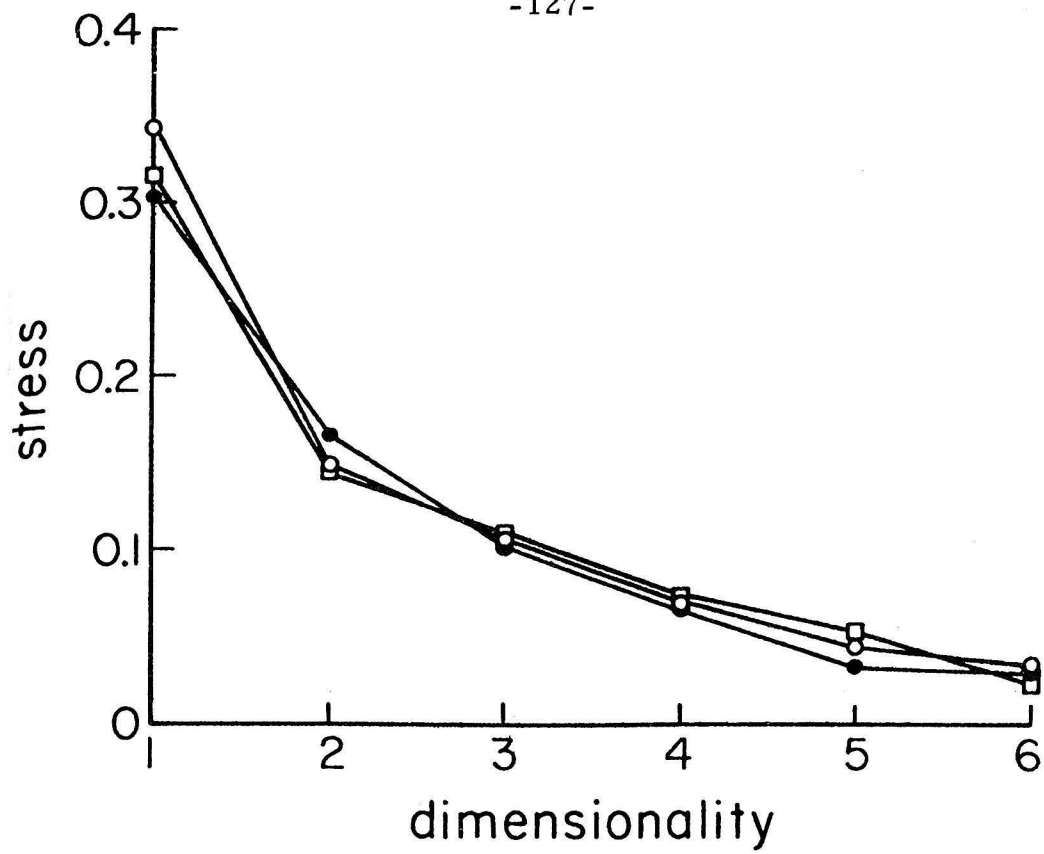


Fig. 5.1 Curves of stress vs. dimensionality and their slopes for three subjects

Key: ● = sub. 1, ○ = sub. 2, □ = sub. 3

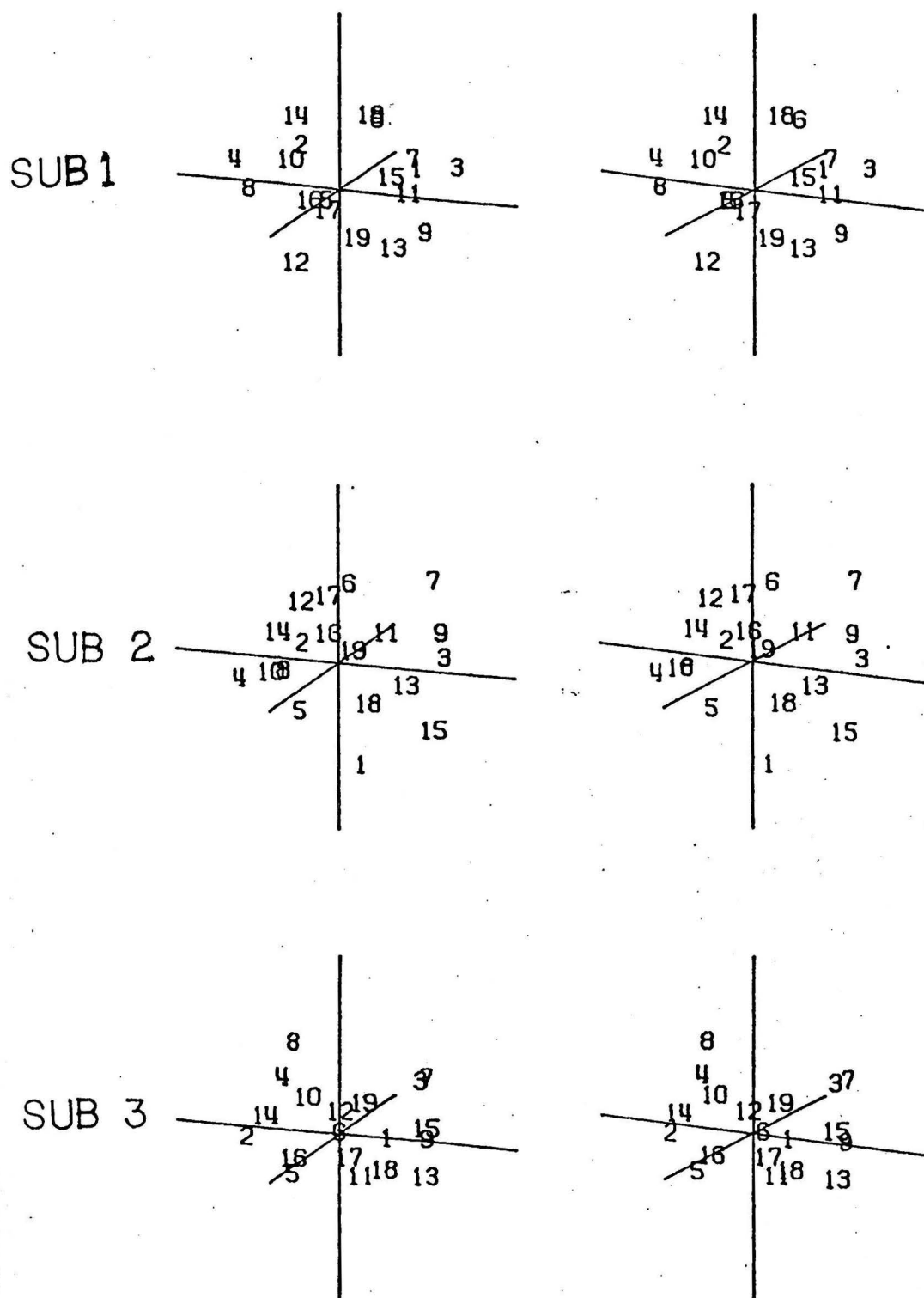


Fig. 5.2 Three-dimensional structures for each sub. Sub. 1 rotated to principal component axes. Sub. 2 and sub. 3 rotated for best fit to sub. 1.

ance occurs (Varimax axes) or no interpoint correlation exists (Principal Component axes). In Fig. 5.2, the configuration for subject 1 has been rotated so that the principal component directions coincide with the axes of the display. The structures for subjects 2 and 3 have been rotated for best fit with the subject 1 configuration. A careful examination of Fig. 5.2 shows that subjects 2 and 3 fit quite well, with certain individual point exceptions, with subject 1. This is to say that the overall interpoint relations of objects within the stimulus group are similar for each subject. Fig. 5.3 shows the principal component directions for all 3 subjects. It can be seen that the principal component directions are different among subjects, especially between subject 3 and the other subjects. The dual results of structural correspondence and principal components dissimilarities indicates the subjects, particularly subject 3, are placing emphasis on different aspects of the stimulus group while at the same time recognizing the existence of a common set of perceptual aspects in the group.

In order to quantify how alike the individual subject configurations are, a scheme of comparing them to randomly generated 3-dimensional structures was implemented. The absolute distance of each configuration point to the origin of the display axes was normalized for a mean length of unity. Three arrays of 19 randomly chosen points falling with an average distance of unity from the origin were selected. The random 3-D structures were rotated against the subject structures in pairs using the algorithm of Marquardt(1963) to determine the relative positions for which the interpoint distances were

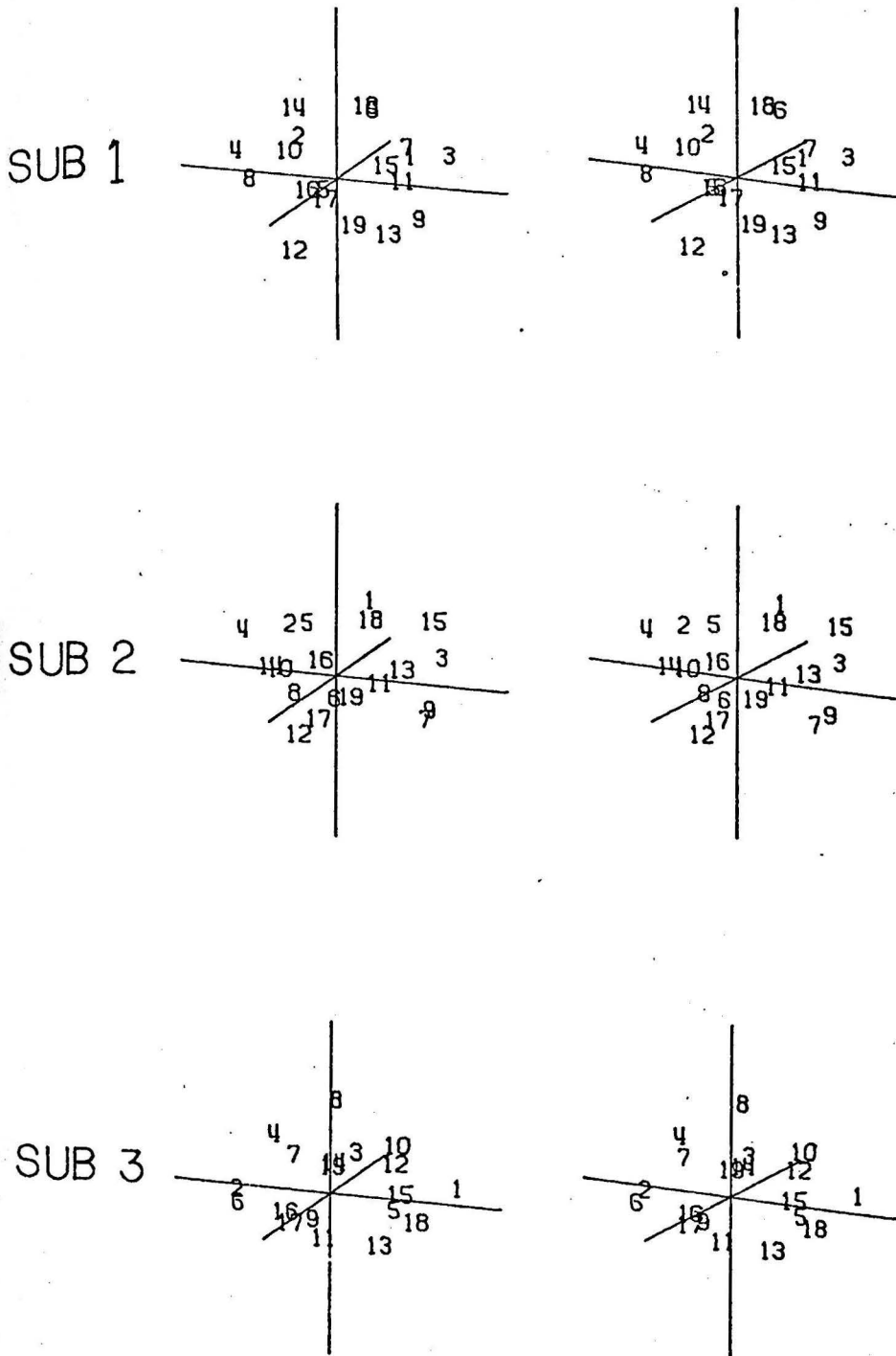


Fig. 5.3 Three-dimensional dissimilarity configurations rotated to principal component axes

minimal. Table 5.1 gives the Sum of the Squares of the Minimal Inter-point Distances (SSMID) remaining between points of two configurations that have been rotated for best fit. The pairs containing one random and one subject configuration have a mean SSMID of 33.368 ± 3.511 (i.e. $\pm$ one standard deviation from the mean). The pairs of two subject configurations fit with much lower SSMID. The values are given in Table 5.1 and it will be seen that all values differ from the random mean by several standard deviations. The correspondence of subject configurations is therefore much better than could be expected to occur by chance.

Most of the 19 points between subjects are close with only a few points having exceptionally different positions. The major amount of the 'badness of fit' between pairs of subjects is caused by a small number of textures. This is shown in Table 5.2. In each of the three rotated pairs, the first 3 textures in the rank order account for about 40% of the total SSMID. On the average, the 4 worst-fit textures are 12, 18, 8 and 1. Each subject apparently had his own individual way of perceiving these textures.

Characterization of Structures

The results of rotating subject 3-D configurations with randomly generated configurations show the subject structures are much more like each other than like random structures. The 19 rules that were used to generate the textures allowed for only directionality and granularity variations; we now have quantitative evidence that these physical differences were perceived in similar ways by all of the sub-

Subject 3D configurations and random configurations

Minimum Squared Distance				
	Subject 1	Subject 2	Subject 3	
Random 1	28.155	27.324	33.136	Mean = 33.368 SD = 3.511
Random 2	34.443	34.307	37.782	
Random 3	33.369	36.426	35.368	

Rotations of subject pairs

Minimum Squared Distance		
		Difference from Random Mean in SD's
Subject 1 vs Subject 2	10.77	6.4
Subject 2 vs Subject 3	13.30	5.7
Subject 3 vs Subject 1	16.31	4.8

Table 5.1 Interrotation of subject and random three-dimensional configurations

Subject 1 vs Subject 2
Total SSMID = 10.77

Subject 1 vs Subject 3
Total SSMID = 16.31

Subject 2 vs Subject 3
Total SSMID = 13.3

texture #	SMID	% of total	texture #	SMID	% of total	texture #	SMID	% of total
18	1.72	15.97	12	2.89	17.72	8	2.86	21.5
12	1.35	12.53	18	2.16	13.24	12	1.59	11.95
8	1.12	10.40	1	1.80	11.04	18	1.23	9.24
19	.85	7.89	9	1.21	7.52	2	1.03	7.74
6	.72	6.68	17	1.19	7.30	5	.85	6.39
1	.70	6.49	19	1.10	6.74	19	.81	6.09
14	.62	5.76	5	1.02	6.25	7	.79	5.94
5	.59	5.48	15	.85	5.21	4	.77	5.79
11	.58	5.39	2	.53	3.25	16	.52	3.90
4	.52	4.82	11	.52	3.19	10	.44	3.31
2	.45	4.17	7	.49	3.00	1	.42	3.15
9	.30	2.79	14	.48	2.94	11	.32	2.41
3	.28	2.60	4	.41	2.51	3	.31	2.33
7	.27	2.50	13	.38	2.33	9	.29	2.18
13	.20	1.86	3	.36	2.21	13	.28	2.11
10	.17	1.58	8	.35	2.15	15	.26	1.95
17	.15	1.40	6	.24	1.47	14	.21	1.58
15	.14	1.30	16	.18	1.10	17	.18	1.35
16	.0081	.08	10	.13	.80	6	.03	.23

Table 5.2 Rank ordering of worst-fit textures

jects. Moreover, we can infer certain things about the discrimination processes from the configurations themselves.

Using our knowledge of the correlation properties of the textures, the following perceptual characterization of the principal component axes for each subject configuration can be formed. The axis of maximum variance for subjects 1 and 2 is strongly associated with texture 3, pVpH, and texture 4, nVnH. From the description of the generating processes, it is apparent that positive correlation in a particular direction would produce strings of like dots along that direction and positive correlation in the two directions would produce clumps of characteristic shape. Likewise, negative correlation would give a fine salt-and-pepper or smoothed-out appearance since there would be continual switching of polarity from dot to dot. The principal components structure tells us more, however. In subjects 1 and 2, textures 3 and 4 are represented almost entirely by one axis; therefore, this axis is associated with the percept of granularity. It will be explained shortly that the other two axes are associated with directionality percepts, but textures 3 and 4 have very small components in these axes and hence, elicit little or no directionality percept. Other textures with two positive correlations or two negative correlations do not have this single axis representation, nor do they display the large granularity component shown by textures 3 and 4. Apparently, two positive correlations or two negative correlations in the vertical and horizontal combine in such a way that their directionality percept is lost and their granularity aspect is enhanced. Directionality combinations other than horizontal and vertical do not elicit pure granularity percepts because

they do not result in complete suppression of directionality components.

The axis with the second most variance of the principal component axes can be associated with the perception of verticality and horizontality, one being treated as the negative of the other. This interpretation is derived from the arrangement of all textures with a positive vertical (pV) correlation on the opposite side of the origin from all textures with positive horizontal (pH) correlation (see Fig. 5.3 and Table 5.3). Textures with nV correlation are aligned alongside the pH textures; those with nH are found together with the pV textures. Indeed, it is clear from looking at the textures that negative horizontal correlation results in a percept of verticality and negative vertical correlation results in a horizontality percept (see textures 2 and 8, Fig. 5.4). However, the approach of representing both vertical and horizontal by a single principal component is not intuitively apparent and only arises from the study of the three-dimensional structures derived by the scaling analysis.

The principal component with least variance in the three-dimensional space of our 19 textures is associated with the diagonality percept. Diagonality has two orthogonal aspects; north-west to south-east and north-east to south-west. These two, just as vertical and horizontal, are associated with a single principal component. Not only is positive diagonal correlation different from negative diagonal correlation by virtue of its granularity, it is also different because of a 90-degree rotation in directionality. The 90-degree directionality difference is represented as a sign change on the principal component axis associated with diagonality.

texture #	subject 1			subject 2			subject 3		
	% of total column variance			% of total column variance			% of total column variance		
	47%	31%	22%	45%	37%	18%	45.4%	38%	16.6%
1	-.99	.53	.38		-1.15	.56	-1.33	-.44	-.03
2	.82	-.71	.20	.23	.98	.72	1.42	-.36	-.27
3	-1.22	-.21	.24	-1.19	-.03	.22	-.47	.63	.58
4	1.37	-.08	.13	1.11	.25	.42	.89	-.30	.48
5	-.20	1.13	.09	.57	-.38	.41	-.42	-.94	-.52
6	-.07	-.90	.55	-.34	1.14	-.02	.95	.64	-.13
7	-.62	-.54	.20	-1.23	.76	-.27	.06	1.15	.62
8	.80	.81	.05	.85	-.65	-.56	.23	-.65	.88
9	-.83	-.36	-.61	-.97	-.33	-.50	-.14	1.09	-.09
10	.53	.52	.33	.97	-.26	-.16	-.37	-.9	.30
11	-.37	-.92	-.34	-.46	.20	-.09	.12	.29	-.58
12	.47	.57	-.84	.60	.07	-.86	-.47	-.53	.17
13	-.62	.43	-.58	-.42	-.73	-.18	-.64	.59	-.50
14	.74	-.16	.68	.71	.61	.11	.43	-.87	.63
15	-.51	.20	.16	-.73	-.92	.41	-.82	.38	.05
16	.68	-.40	-.40	.11	.62	.24	.81	-.20	-.45
17	.44	-.38	-.50	.19	.47	-.51	.51	.38	-.40
18	-.33	.34	.87	-.16	-.29	.53	-.84	-.15	-.41
19	-.09	.11	-.62	.10	-.38	-.46	.06	.18	.26

Table 5.3 Principle components in three-dimensions for each subject

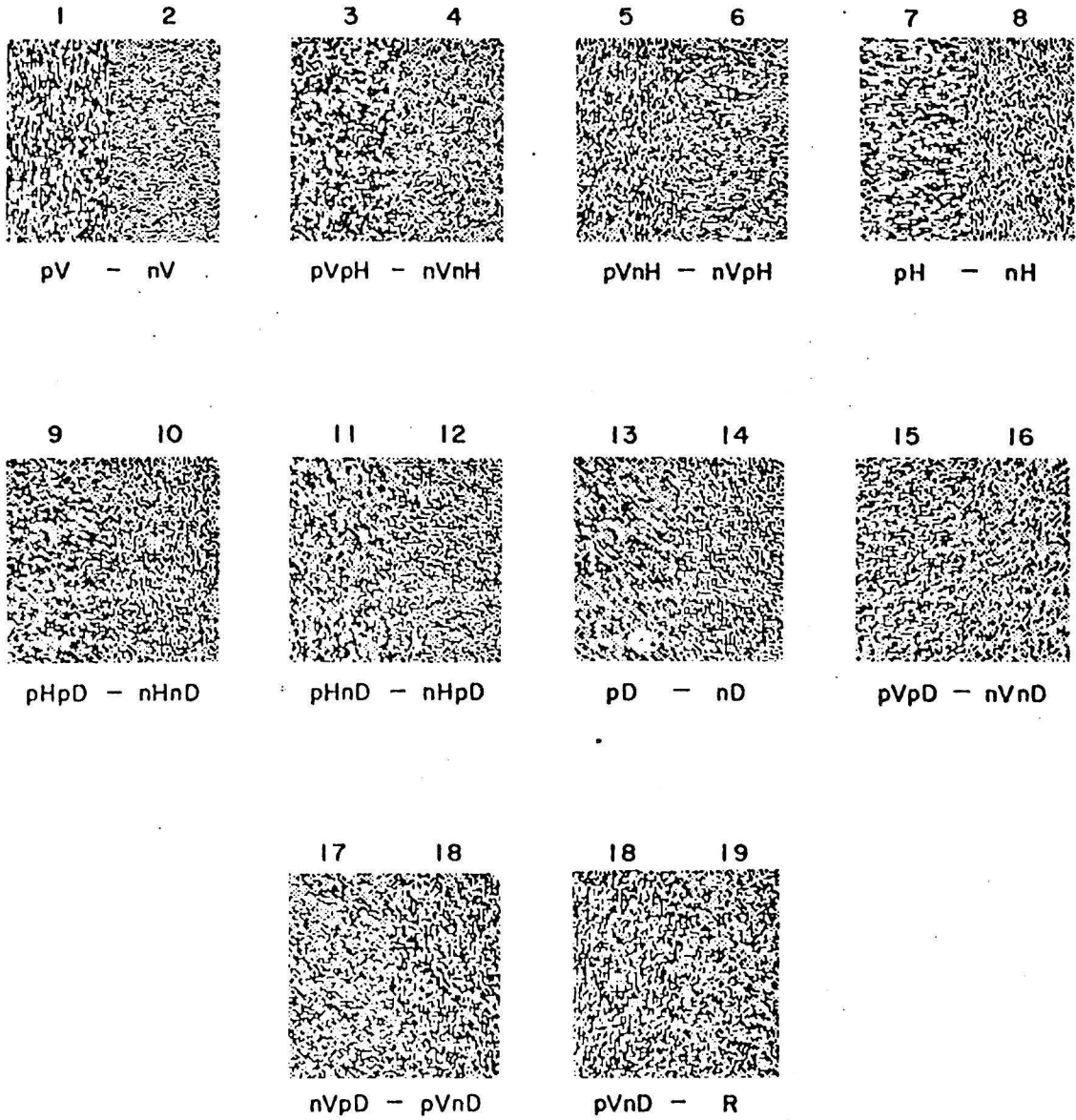


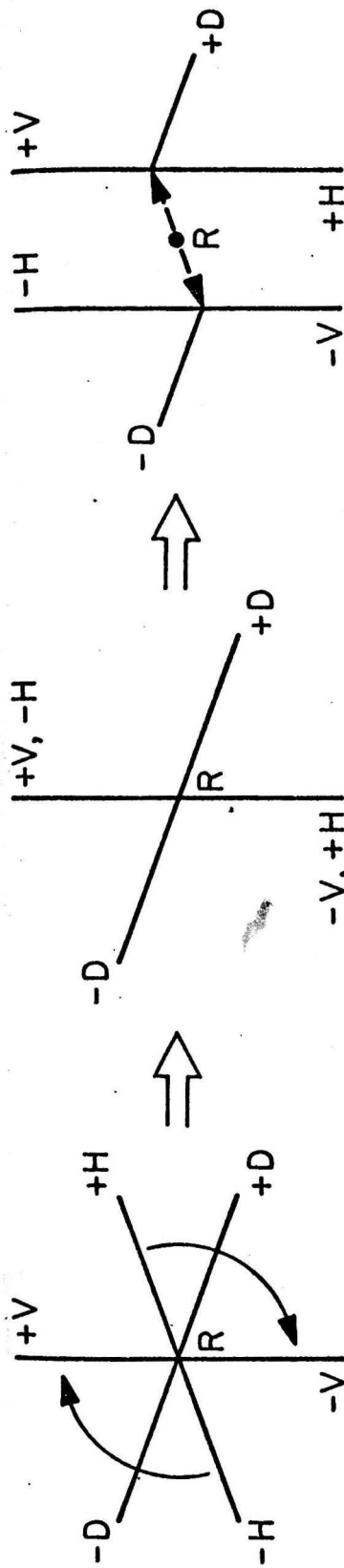
Fig. 5.4 Examples of each texture in the 19-member stimulus group

The fact that diagonality is associated with the least significant of the three principal component directions is indicative of relative weakness in the diagonality sense at perceptual levels as suggested by Attneave and Olson (1967).

Of the textures which seriously violate the common intersubject structure (12, 18, 8 and 1) two have a diagonal component. Interestingly enough, 12 and 18 (nHpD and pVnD) are combinations respectively of nD and pD correlation with textures 1, (pV) and 8, (nH). Textures 1 and 8 theoretically have the same directionality percept (vertical) and differ only in granularity. Textures 12 and 18 conversely have the same granularity and their only directionality difference comes from the nD-pD components. Hence, the diagonality percept is involved in the intersubject discrepancies.

Relation of Physical to Perceptual Space

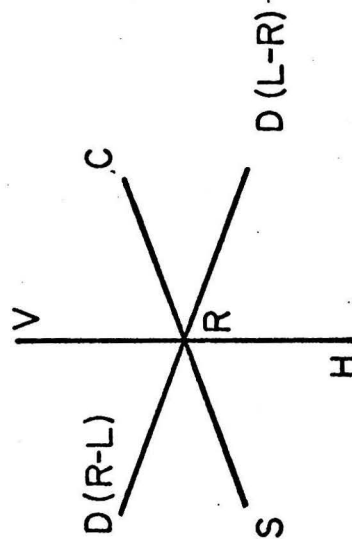
Clearly, some rather unexpected operations have been performed on the original space of physical parameters describing the stimulus group. As shown in Fig. 5.5, the transformation from physical correlation space to perceptual space is done by the introduction of two critical concepts. First, one axis of correlation space is collapsed due to the fact that positive vertical correlation and negative horizontal correlation are identical in the directionality percept each elicits; likewise, for pH and nV. Thus, the perceptual space of our subjects requires only two orthogonal axes to describe the four physical directions, vertical, horizontal and two diagonals, present in our stimulus group. The implication here is that orthogonal directions such as vertical and horizontal are handled by the same percep-



1) Original physical correlation space

2) Vertical and horizontal axes collapse to form one directionality axis

3) Granularity axis is introduced to separate clumpy-smooth percepts



4) Final perceptual 3 space

Fig. 5.5 Transformation from physical correlation space to perceptual space.

tual rule(perhaps acting in different modes for the two directions).

The perceptual space describing the stimuli does have a third axis (a very significant one) which is totally direction independent; it is the granularity axis. Granularity is seen in the first case to be concerned with the sign of the correlation in a particular direction. If a texture has positive correlation, it will have clumps of like dots. Negative correlation gives a smoothed-out percept which is the direct opposite of clumpiness. All subjects perceived the stimuli as divided into two groups; patterns with positive correlation and patterns with negative correlation. The principal components analysis tells us that the clumpy vs. smooth distinction was the primary discriminant for two of the three subjects.

The granularity percept is not simply related to the amount of dot to dot correlation in a given pattern. For example, texture #3, pVpH, has the same total amount of positive correlation as texture #1, pV. The correlation in texture #3 is evenly divided in the two physical directions V and H while texture #1 has all its correlation in the vertical. Texture #1 elicits both verticality and granularity percepts. Texture #3 stimulates only the granularity percept and does so with significantly more strength than texture #1. Likewise, when negative correlation is present, if it is evenly divided in two orthogonal directions (i.e. nVnH), it elicits a pure granularity percept which is stronger than if it is concentrated in one direction only (nV for example).

Rather a different phenomenon is seen in cases where the correlation in orthogonal directions is of opposite sign such as texture #5,

pVnH. The granularity percept of texture #5 is approximately the same as for the texture with no correlation in any direction, #19. It can be concluded that correlations of opposite sign in orthogonal directions cancel each other as far as overall granularity strength is concerned. However, the directionality percept is quite enhanced when opposite signed correlations in orthogonal directions are combined. An example of directionality enhancement occurs with texture #5. In all subjects, texture #5 defines one extreme of the vertical/horizontal directionality axis; it has significantly more strength in eliciting a verticality percept than texture #1, which contains only positive vertical correlation.

Perceptual Model

Thus, a model of the combinatorial mechanisms for the conversion of physical pattern characteristics into perceptual discriminants begins to take shape. The model is now defined in the form of a set of rules for the perceptions elicited by the addition or subtraction of connectivity from a field of black and white dots that initially contains an equal amount of connectivity in all directions (a field with $C_2(1) = 0$ in all directions for example).

1. Addition (subtraction) of connectivity in one direction gives a percept of clumpiness (smoothness) in that (the orthogonal) direction.
2. The simultaneous addition (subtraction) of connectivity in two orthogonal directions gives a percept of clumpiness (smoothness) only; no directionality percept.

3. The simultaneous addition (subtraction) of connectivity in two oblique directions gives simultaneous independent percepts of clumpiness (smoothness) in each direction.
4. The simultaneous addition of connectivity in one direction and subtraction of connectivity from the orthogonal direction gives a strong percept of the former direction while leaving the granularity aspect of the field unchanged.
5. The simultaneous addition of connectivity in one direction and subtraction of connectivity in an oblique direction leaves the granularity percept unchanged while eliciting simultaneous independent percepts of the former direction and the direction orthogonal to the latter direction.

In the above rules, it is assumed that equal quantities of connectivity as defined in terms of nearest neighbor dot correlations are used.

A basic result of these rules is that simultaneous connectivity in two orthogonal directions is perceived only in terms of its effect on overall field granularity and elicits no directionality percepts. Connectivity in two oblique directions does elicit simultaneous directionality percepts although for some reason the diagonality percept is always weaker than either the vertical or the horizontal. Hence, a field containing connectivity in oblique directions has the potential to convey more information to an observer since it elicits two independent directionality percepts.

The model described by the five rules just formulated could be expressed in more detail and perhaps could even be translated into hypothetical neural mechanisms for the perception of connectivity

in random dot arrays. The interested reader need only refer to the prolific work on neural modeling by Grossberg (1970a, 1970b) for a glimpse of how such a line of research may be pursued. It is not the intent of the present study to delve into very involved neural models for the psychophysical experiments just presented. The results just obtained form the basis for selection of several patterns from the stimulus group to be used in evoked potential experiments.

The thrust of the VESP study is to determine the effects (if any) of different statistical arrangements of dots in a texture field on the scalp potentials evoked by visual stimulation with that field. In short, the question to be answered is can differences in the statistics of visual field stimuli be inferred from measurements of the electric fields on the scalp of a subject viewing those stimuli. A first hypothesis in this regard was that if the subject himself could perceive no difference between two patterns generated by different statistics, then there probably would be no differences in the scalp potentials evoked by the two patterns. Thus, in the first case, the psychophysical study was launched with the aim of determining the patterns of our stimulus group which were perceptually most different to our VESP subjects.

The most different patterns for each subject are listed in Table 5.4. The present analysis of principal components in the stimulus group leads to a second criteria for selecting patterns for VESP testing. A rank ordering of the more prominent patterns in each principal component is also shown in Table 5.4. We now can ask the question; will textures that are different only in their relative magnitude along the same principal component yield very different VESP's or must textures contain

Ranking of texture pairs by separation in 3-space

Sub. 1	Sub. 2	Sub. 3
3-4	8-7	2-1
4-1	7-4	1-6
4-9	7-1	5-7
3-8	7-10	2-15
1-2	1-6	2-3
4-13	4-9	1-4

Ranking of textures along 3 principal components

Sub. 1			Sub. 2			Sub. 3		
P1	P2	P3	P1	P2	P3	P1	P2	P3
4	5	18	2	7	8	7	1	12
3	11	12	1	9	14	3	6	2
1	6	13	6	5	7	4	2	8

Table 5.4 Ordering of most different textures for each subject by separation and principal component axis

large amounts of orthogonal components to evoke significantly different scalp potentials? With these two criteria in mind, several of the most different textures were chosen for VESP experiments on our three subjects; the results of those tests will now be presented.

Contour Maps of Scalp Potentials

Fig. 5.6 shows a sequence of scalp equipotential contours at 12 ms intervals over the time course of the appearance/reversal response for the 22 electrode array data set of subject 3. Corresponding to the wave forms shown in Chapter III for subject 3, the equipotential maps show coherent negative activity with large gradients at times when the wave forms show large negative peaks. There are two regions of highly correlated negative activity following the pattern reversal while there is only one such region following pattern appearance. Fig. 5.7a shows 6 frames of subject 3 contour maps which display the peak levels of the response to the appearance of texture 1. In Fig. 5.7b is shown the first negative peak response to texture 1 reversal. Figs. 5.8, 5.9 and 5.10 show the peak response sequence for textures 2, 7 and 6 appearance. The maps show a steep potential gradient centered over theinion with perhaps a small amount of bias toward the right occipital lobe. Figs. 5.11, 5.12 and 5.13 show the first peak response sequence of contour maps for pattern reversal of textures 2, 7 and 6. The first peak of the reversal response for most of the stimulus patterns is quite similar in both waveshape and contour map to the single appearance response peak. Hence the decision was made to restrict analysis to the first (and only) appearance peak response and the first reversal peak.

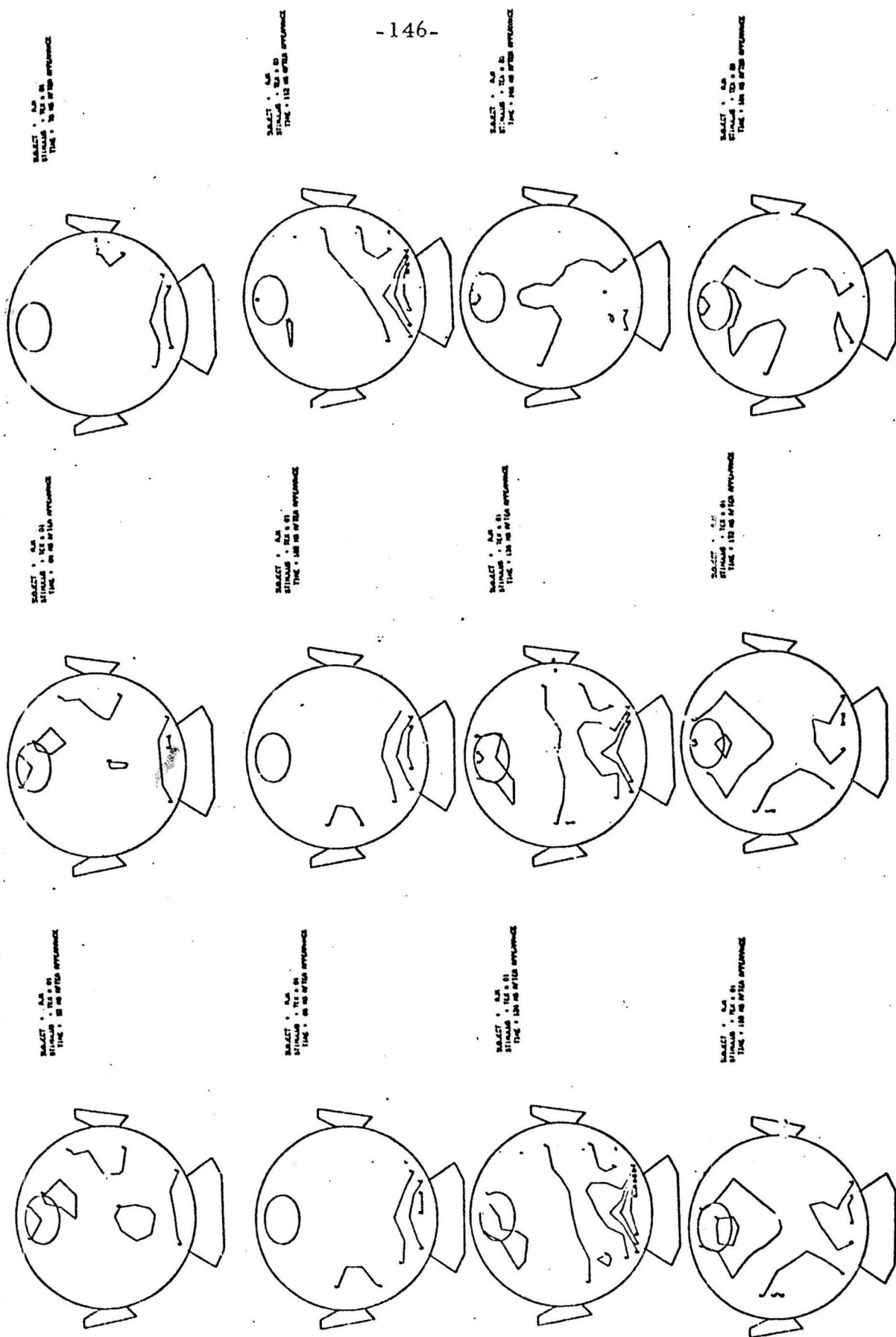


Fig. 5.6a Sub. 3 Tex. 1 52-184 ms after appearance

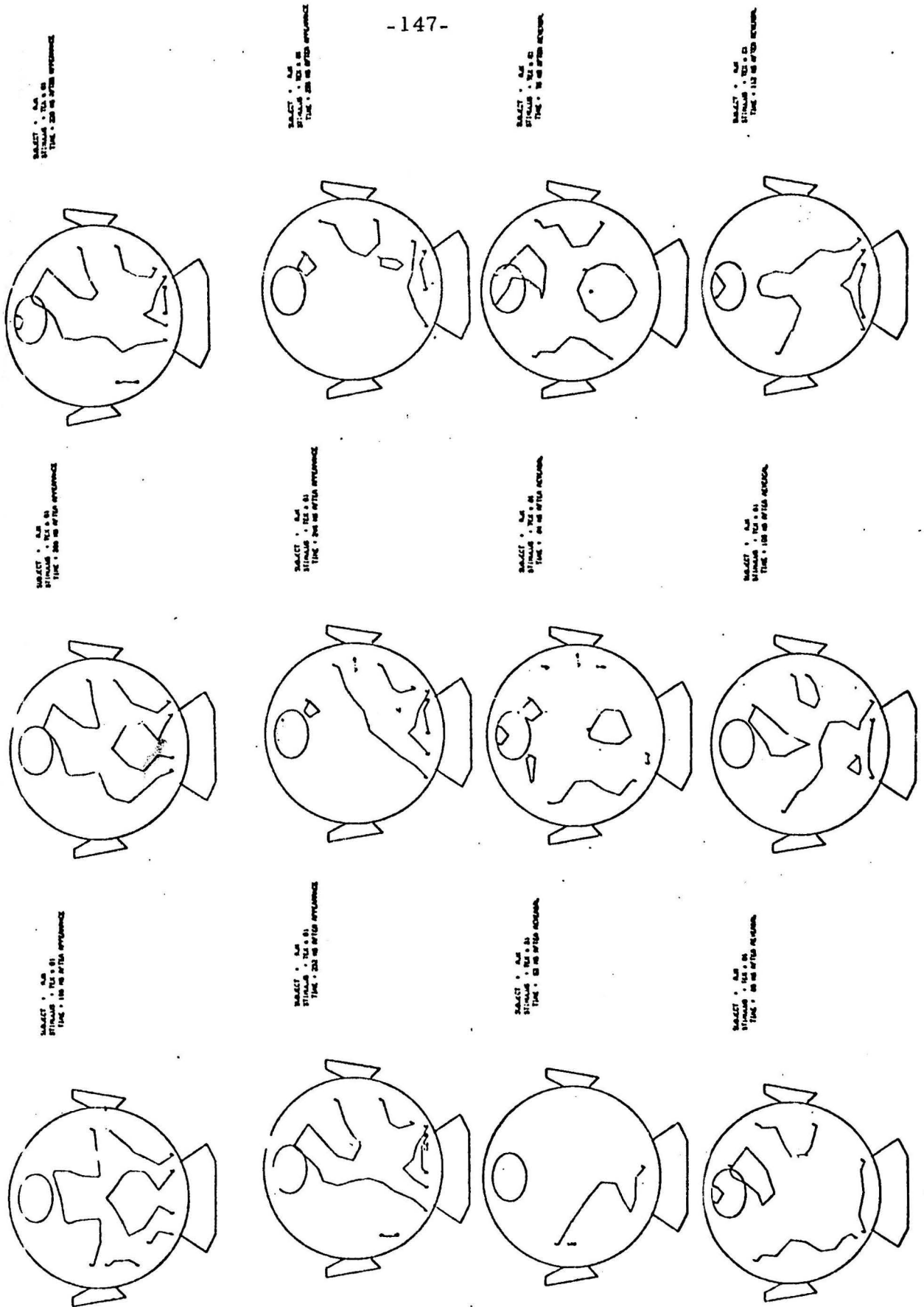


Fig. 5.6b Sub. 3 Tex. 1 196 ms after appearance-112 ms after reversal.

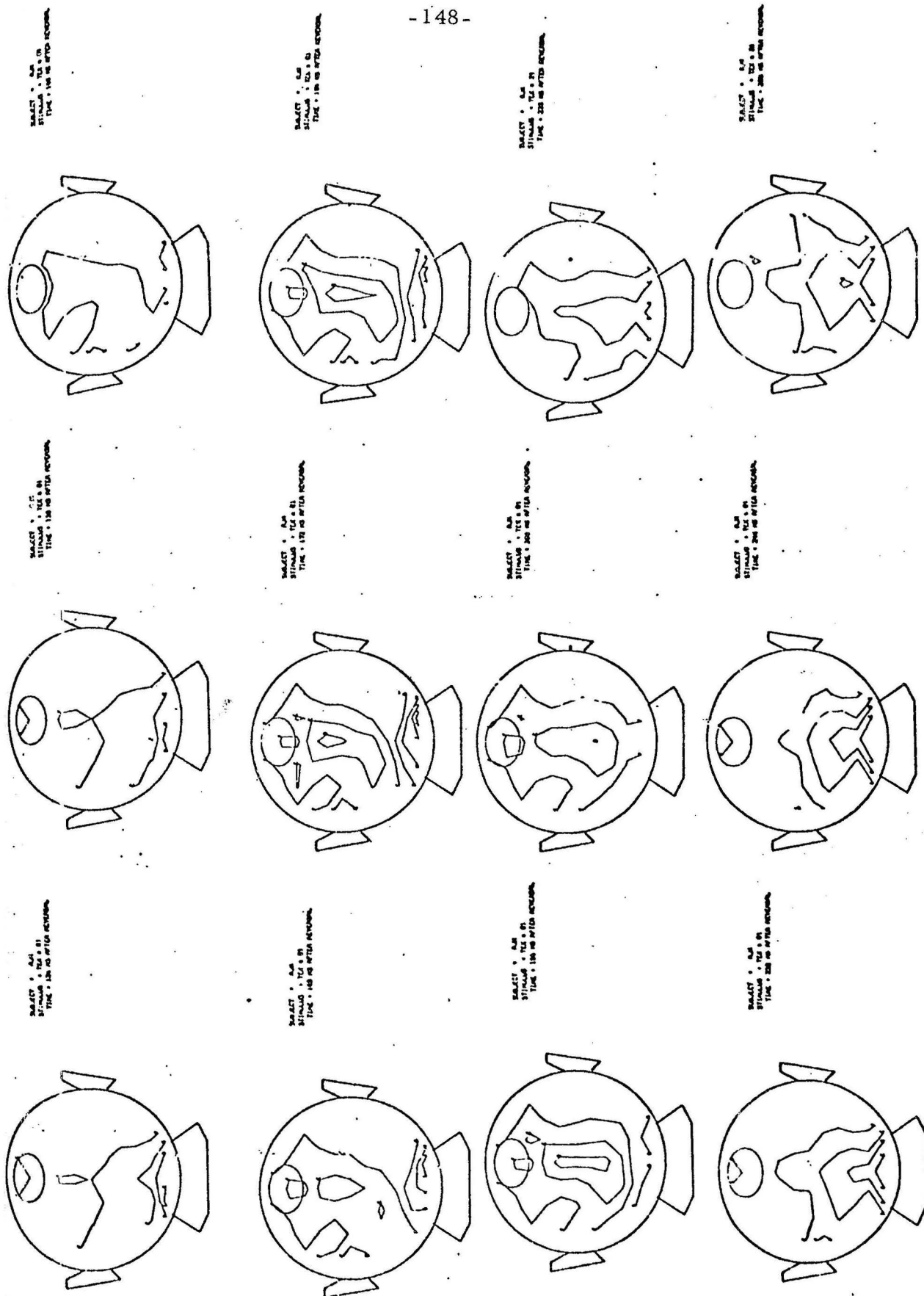


Fig. 5.6c Sub. 3 Tex. 1 124-256 ms after reversal

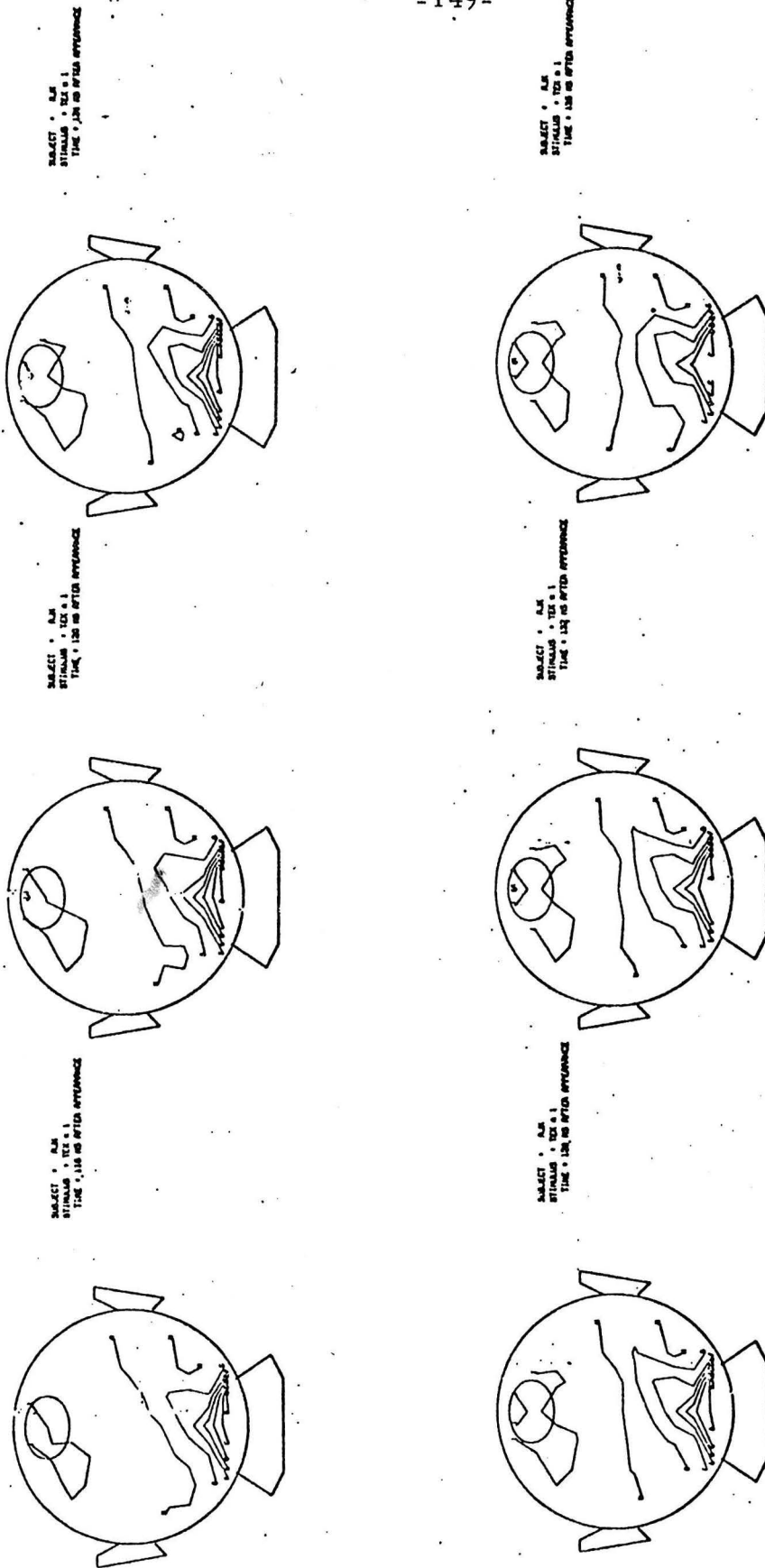


Fig. 5.7a Sub. 3, Tex. 1 116-136 ms after appearance

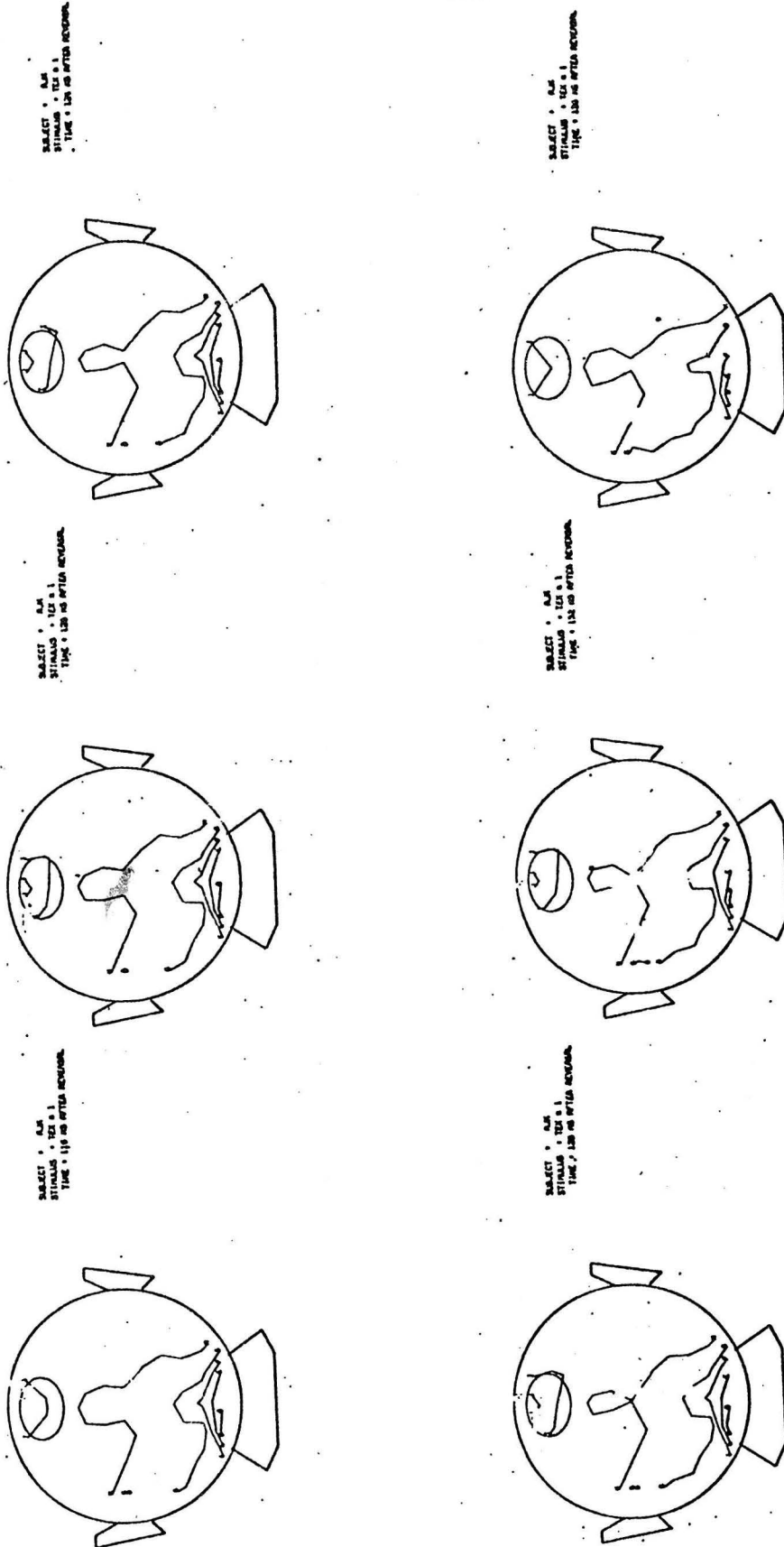


Fig. 5.7b Sub. 3 Tex. 1 116-136 ms after reversal

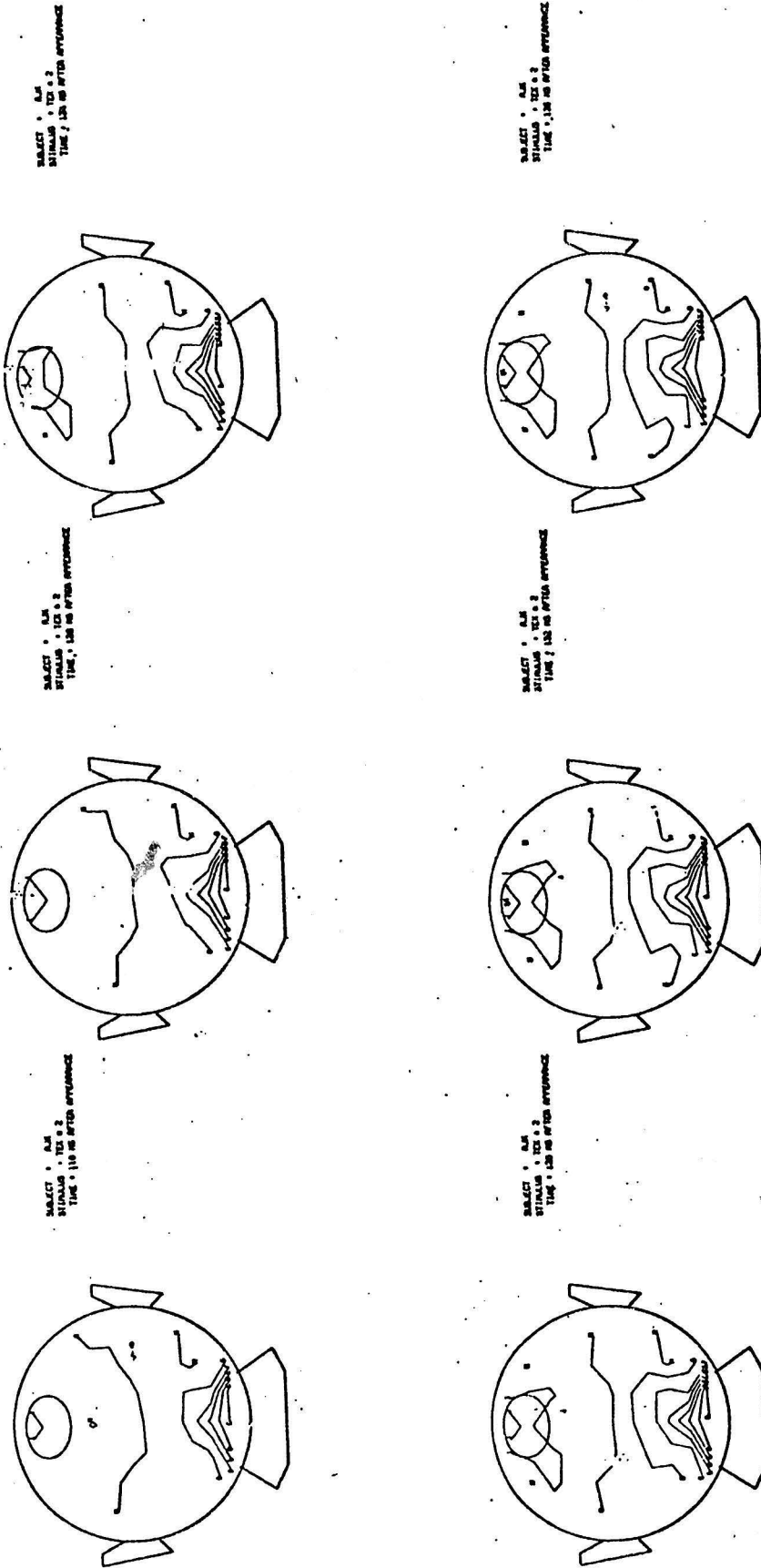


Fig. 5.8 Sub. 3 Tex. 2 116-136 ms after appearance

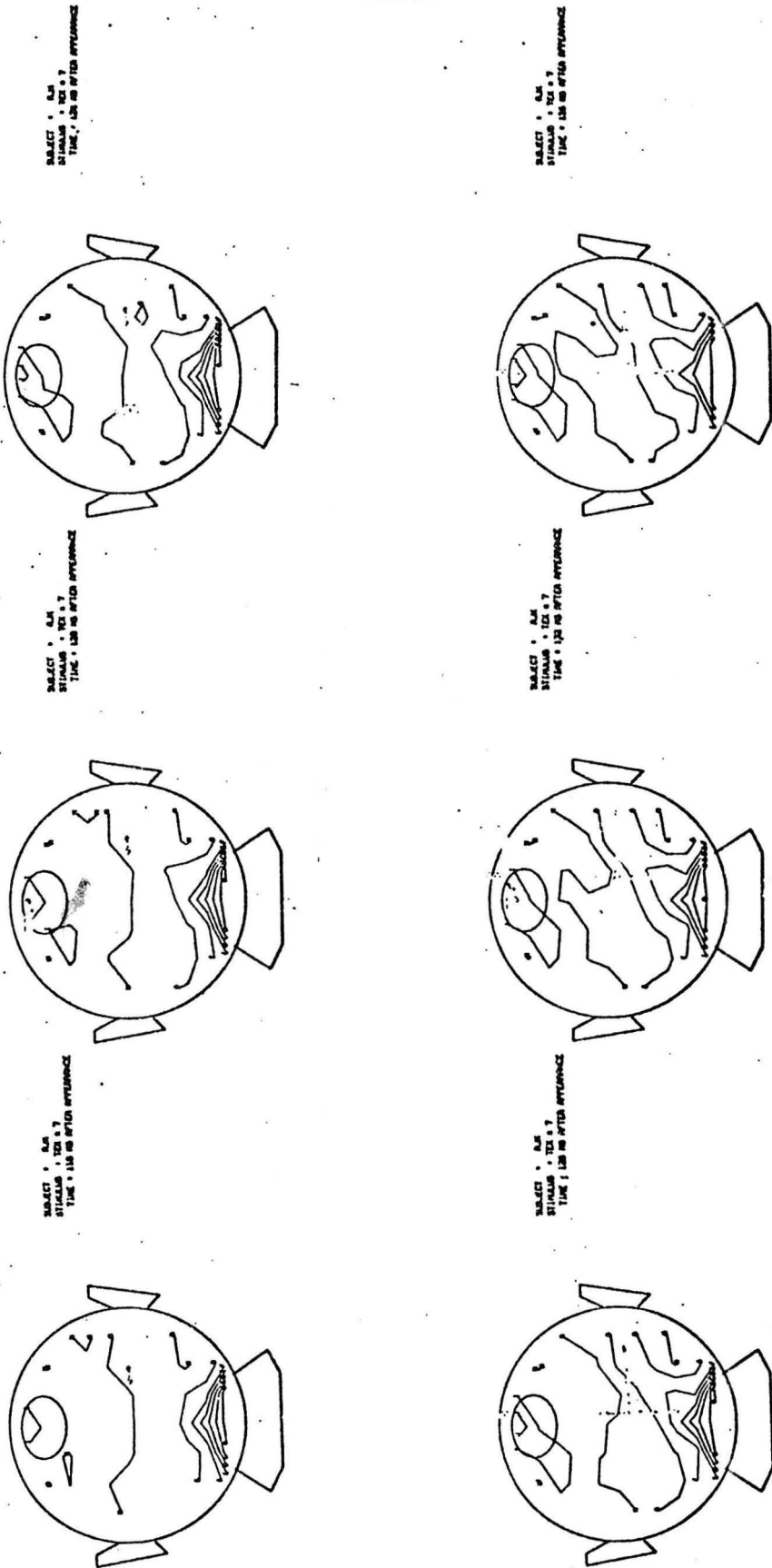


Fig. 5.9 Sub. 3 Tex. 7 116-136 ms after appearance

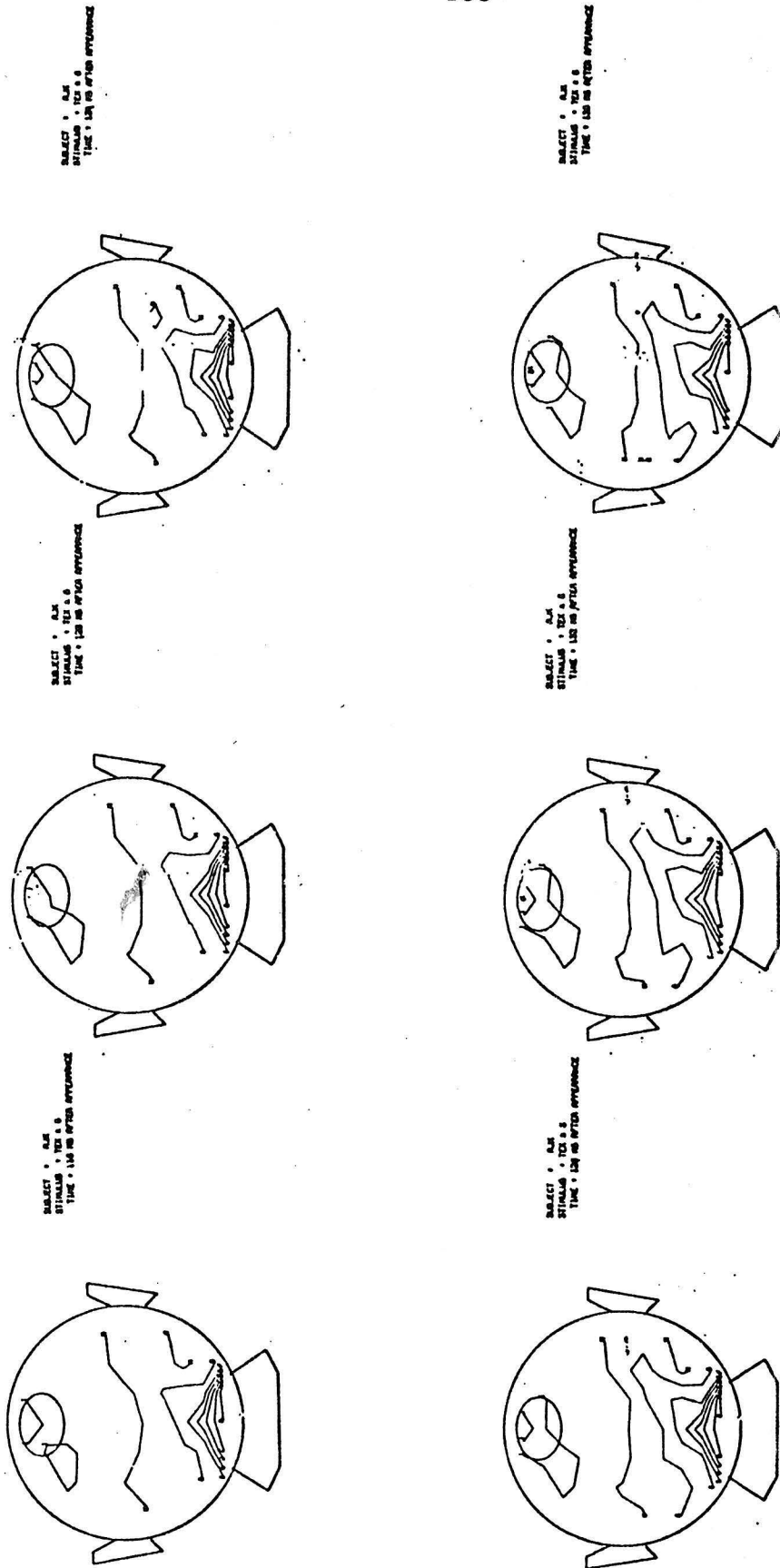


Fig. 5.10 Sub. 3 Tex. 6 116-136 ms after appearance

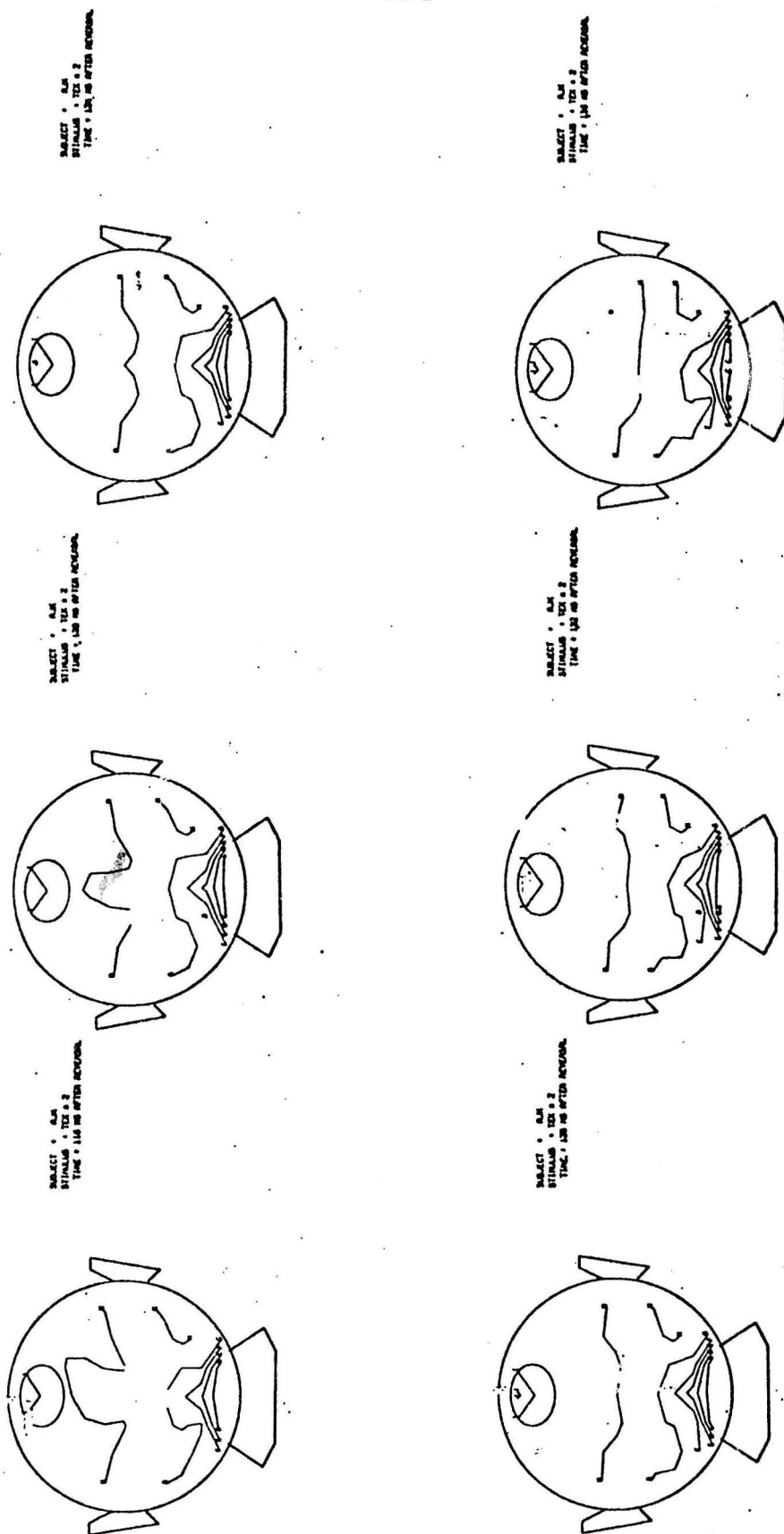


Fig. 5.11 Sub. 3 Tex. 2 116-136 ms after reversal

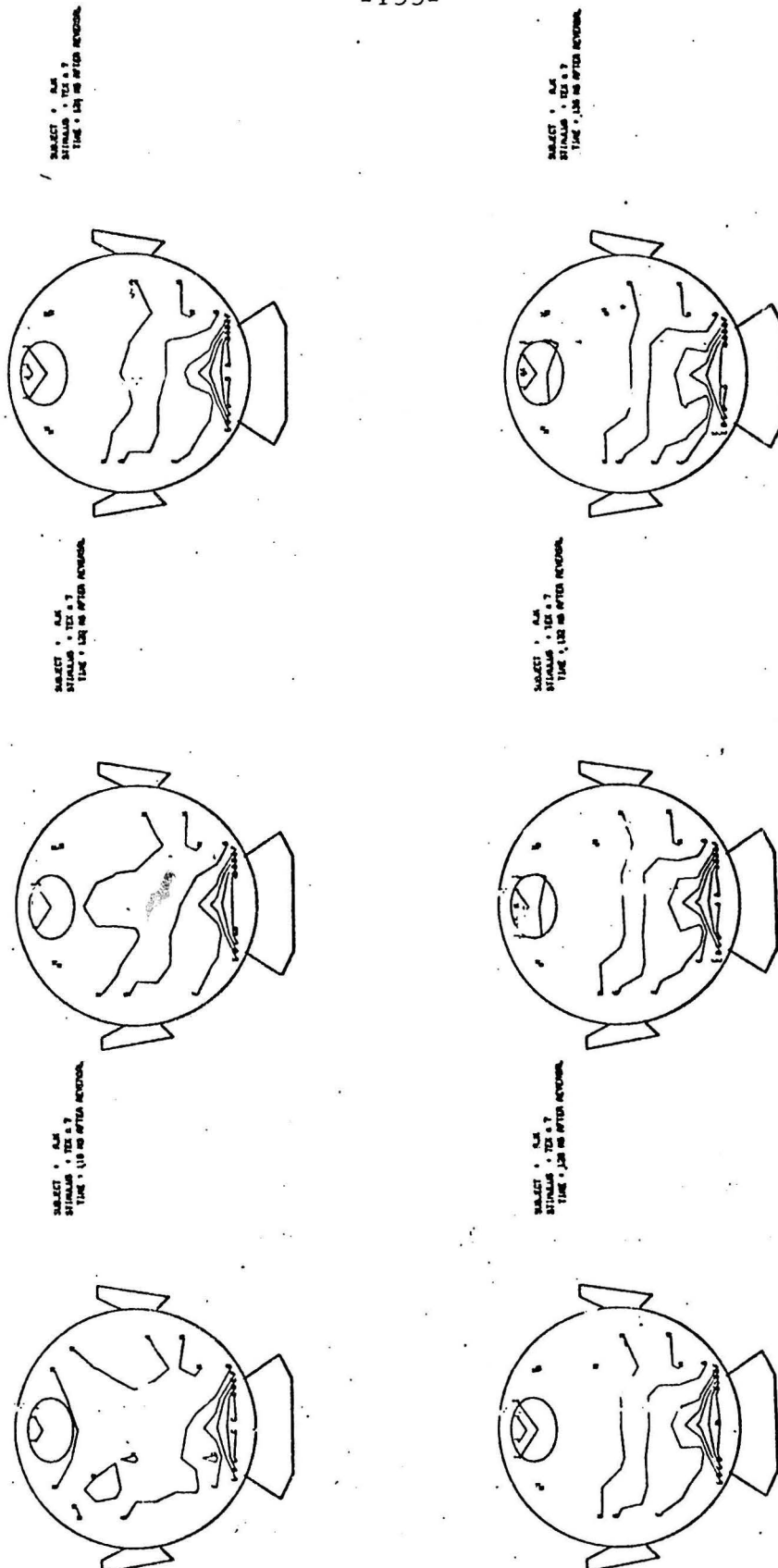


Fig. 5.12 Sub. 3 Tex. 7 116-136 ms after reversal

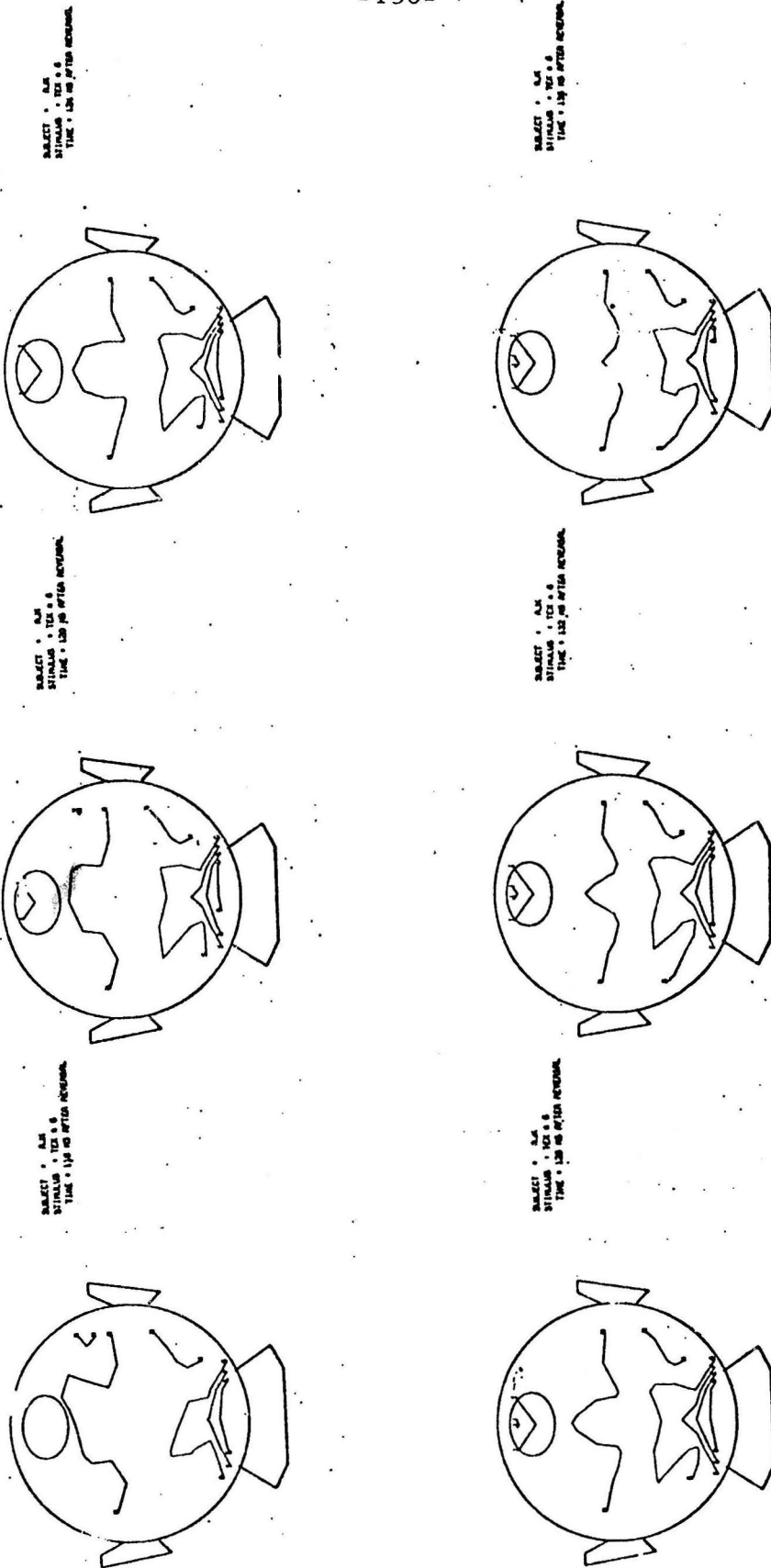


Fig. 5.13 Sub: 3 Tex. 6 116-136 ms after reversal

Careful inspection of the contour maps for each stimulus reveals few differences of significance among them. Some shifts of latency and absolute strength of the peak response seem to be the major variation in the responses to the different textures. The maps strongly suggest that the nature of the response is quite coherent and well-correlated over the space covered by the electrode array. Theinion electrode and its 2 or 3 nearest neighbors register the major focus of the scalp activity. The signals and hence the contour levels at the other electrode sites are uniformly decreasing with distance from the inion. These maps reflect the signal-to-noise ratio distribution at each electrode site shown in Chapter III.

The response contour maps for subjects 1 and 2 at the critical latencies following appearance and reversal events are shown in Figs. 5.14 through 5.25. There are significant differences among the equipotential maps for each subject, just as there are differences among the corresponding electrode waveforms. The evoked potential maps are characteristic of the individual subjects. Nevertheless, the basic behavior, single active peak following appearance event and double peak following reversal event, is discernible in each subject's response.

Visual inspection of each subject's equipotential maps for the different texture patterns shows few strong differences among the individual responses. One can discern variations which lead to a strong feeling that some numerical comparison of the responses for different textures would uncover differences among them. A crosscorrelation of the contour maps would perhaps be a sufficiently sensitive test to reveal any

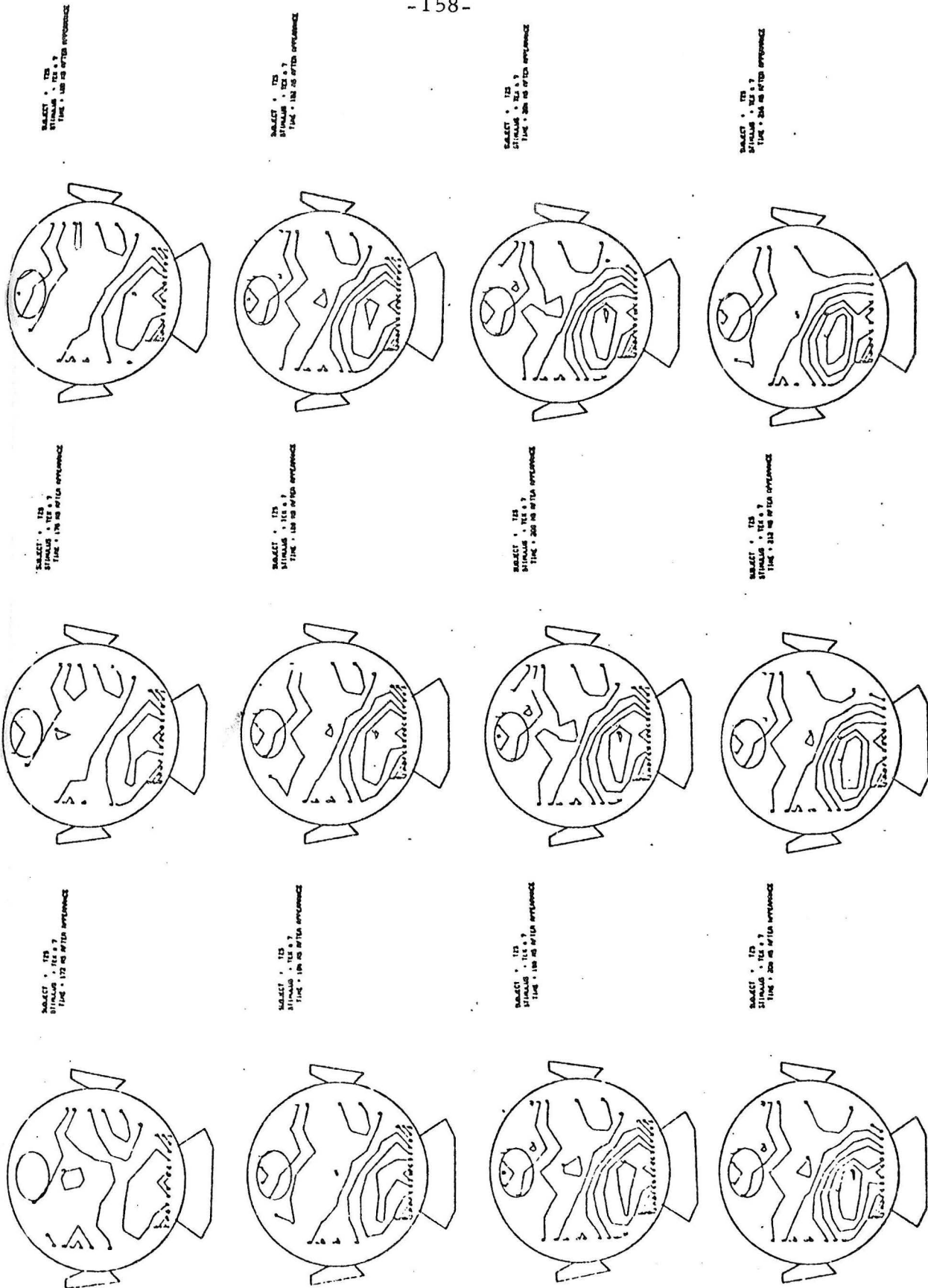


Fig. 5.14 Sub. 2 Tex. 7 172-216 ms after appearance

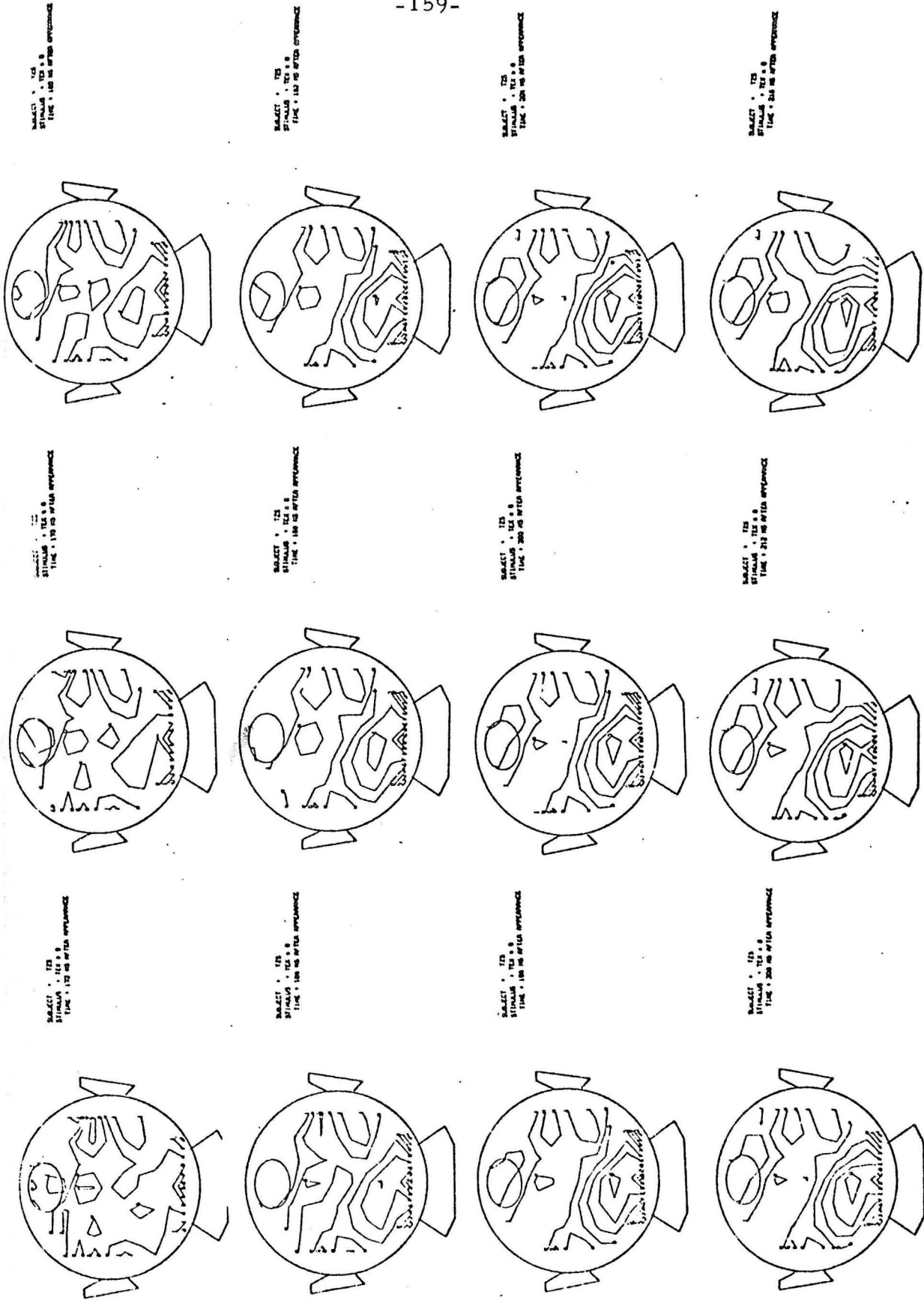


Fig. 5.15 Sub. 2 Tex. 8 172-216 ms after appearance

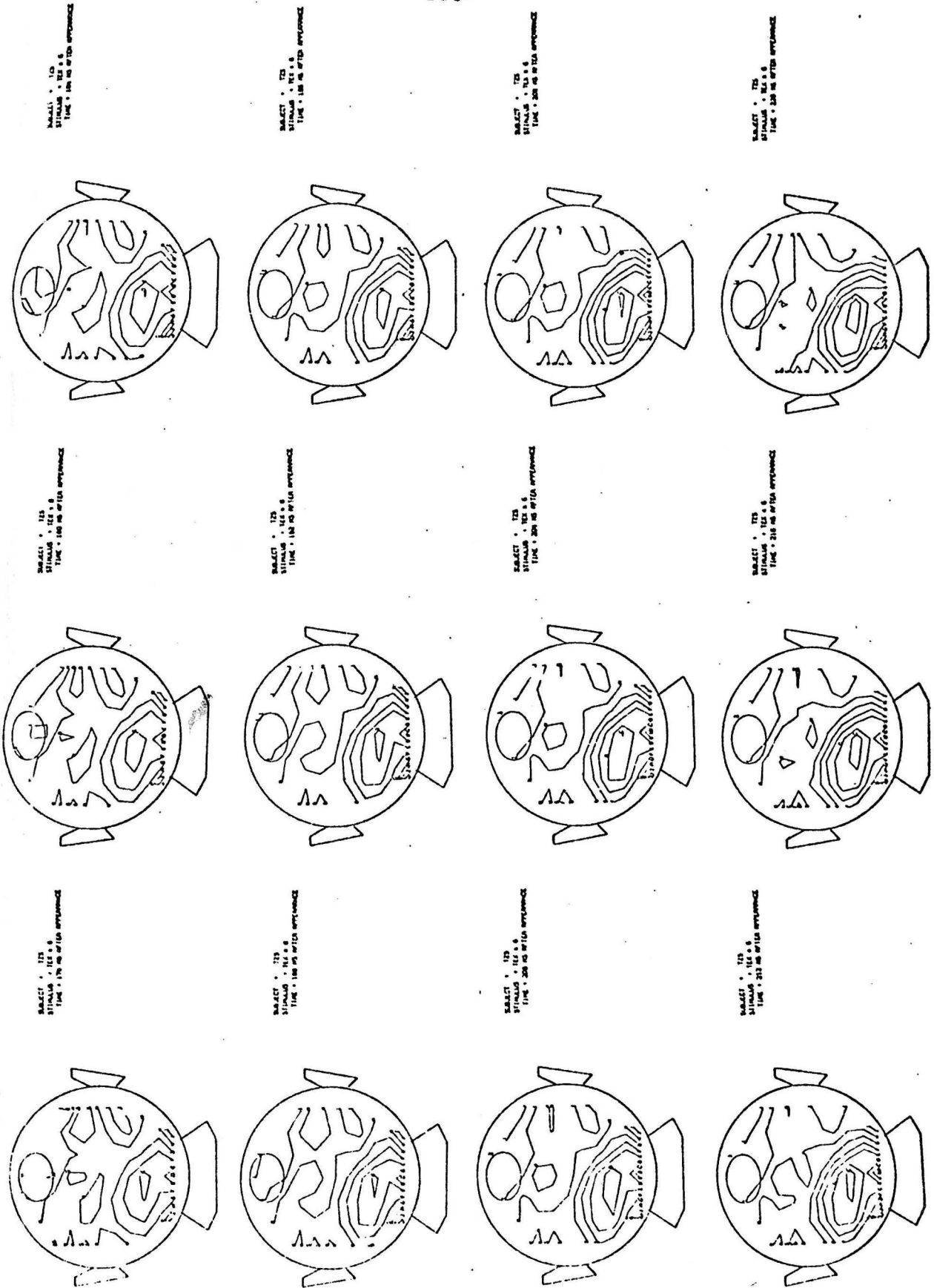


Fig. 5.16 Sub. 2 Tex. 6 176-220 ms after appearance

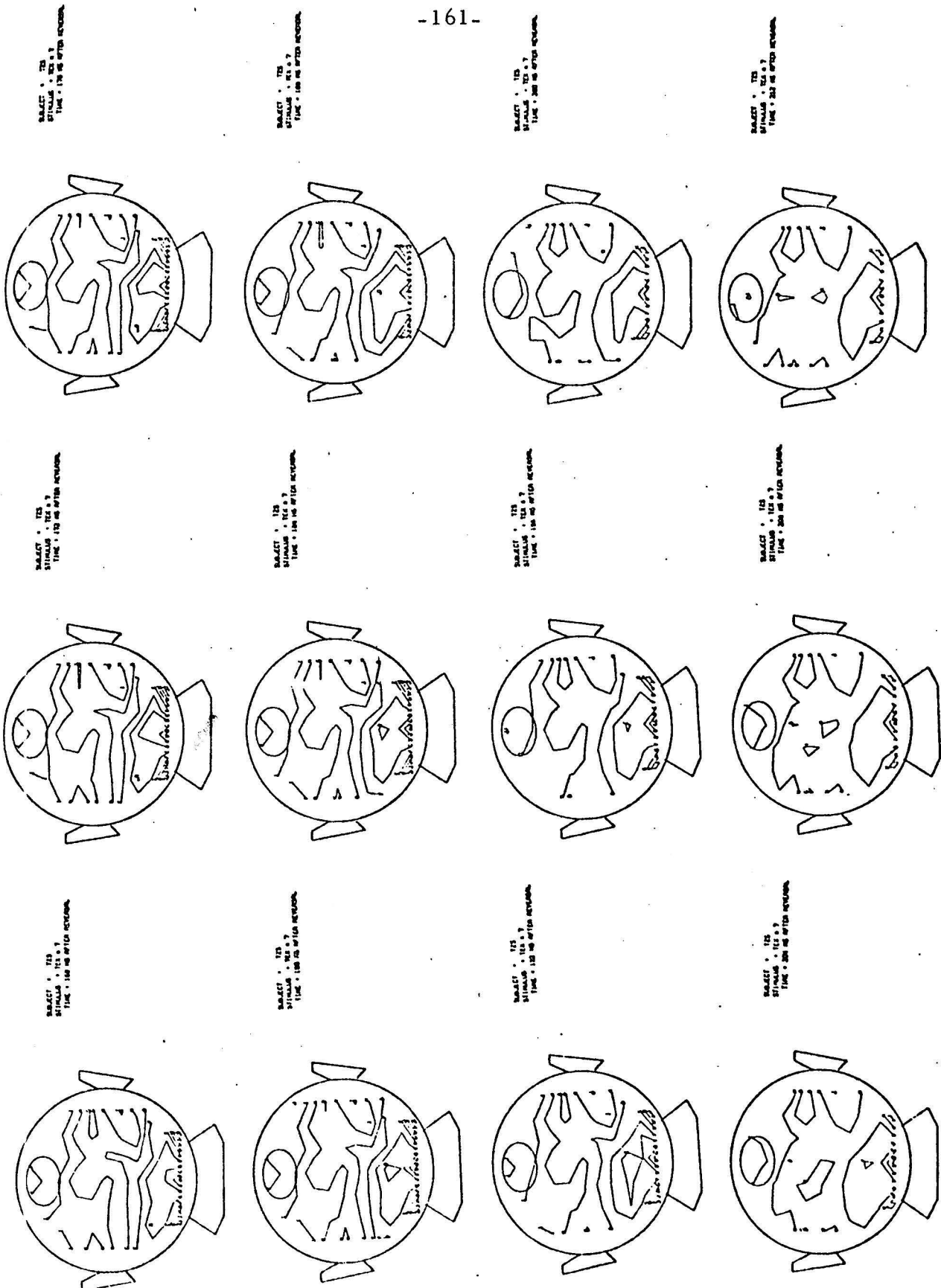


Fig. 5.17 Sub. 2 Tex. 7 168-212 ms after reversal

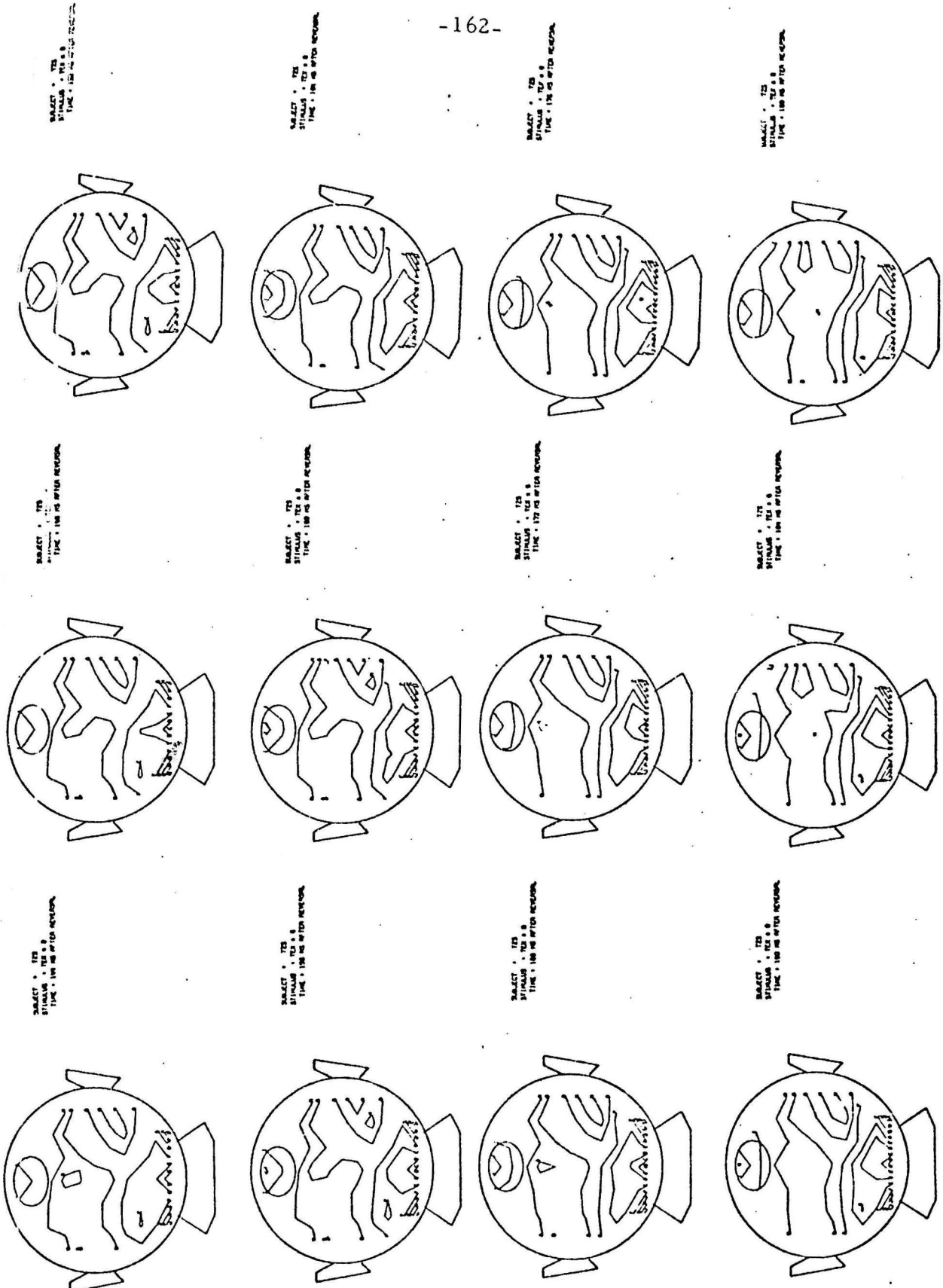


Fig. 5.18 Sub. 2 Tex. 8 144-188 ms after reversal

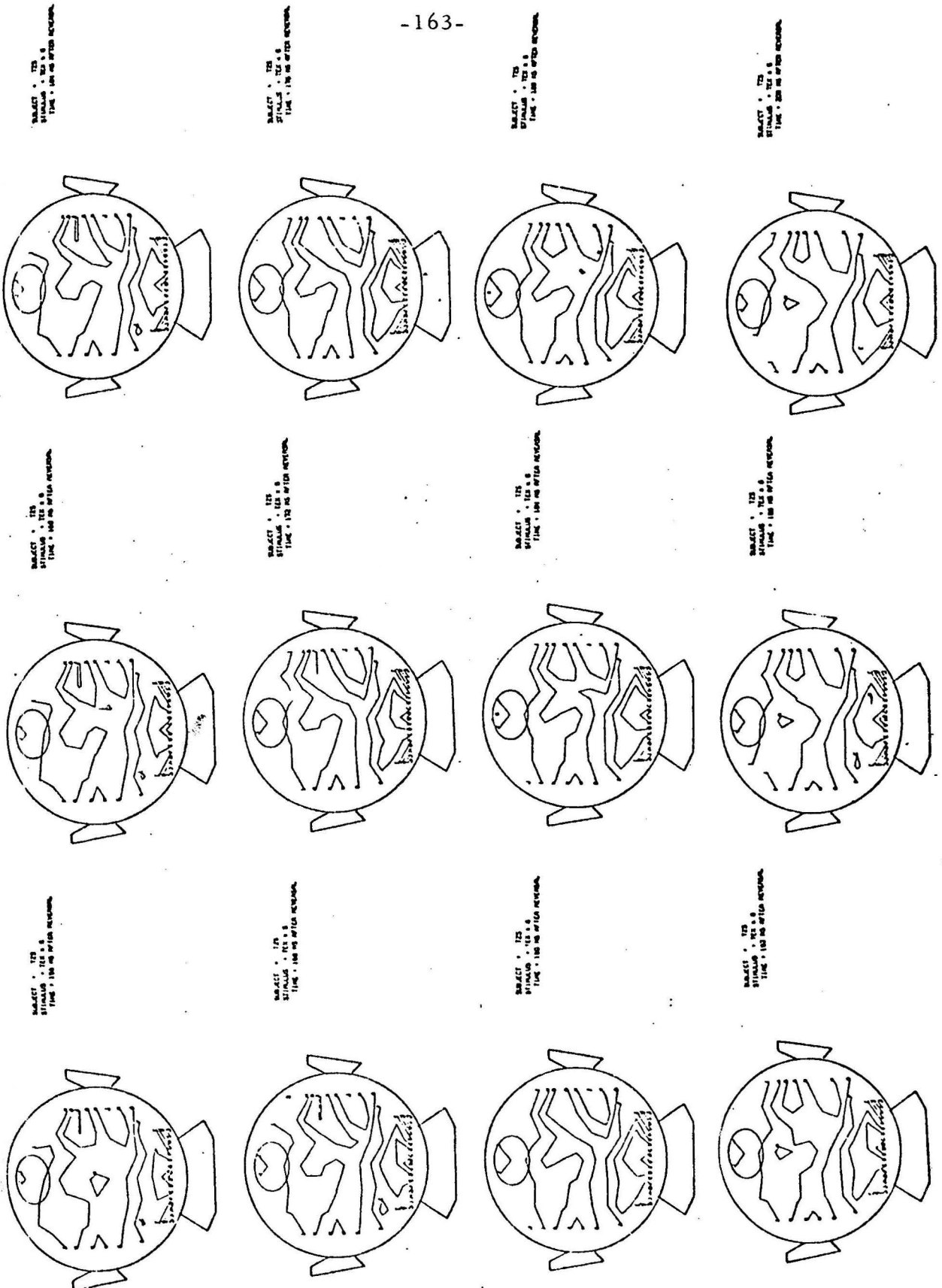


Fig. 5.19 Sub. 2 Tex. 6 156-200 ms after reversal

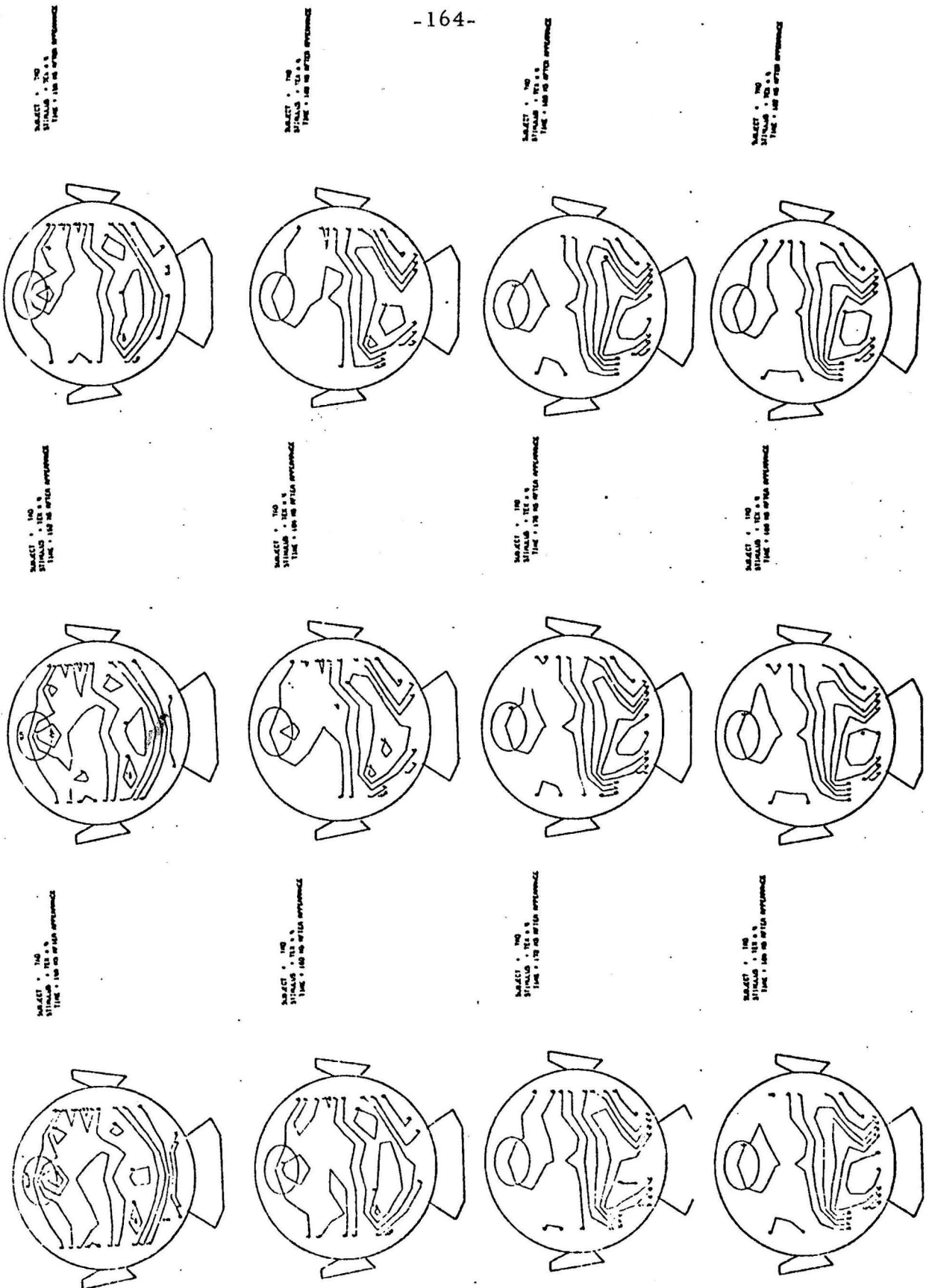


Fig. 5.20 Sub. 1 Tex. 4 148-192 ms after appearance

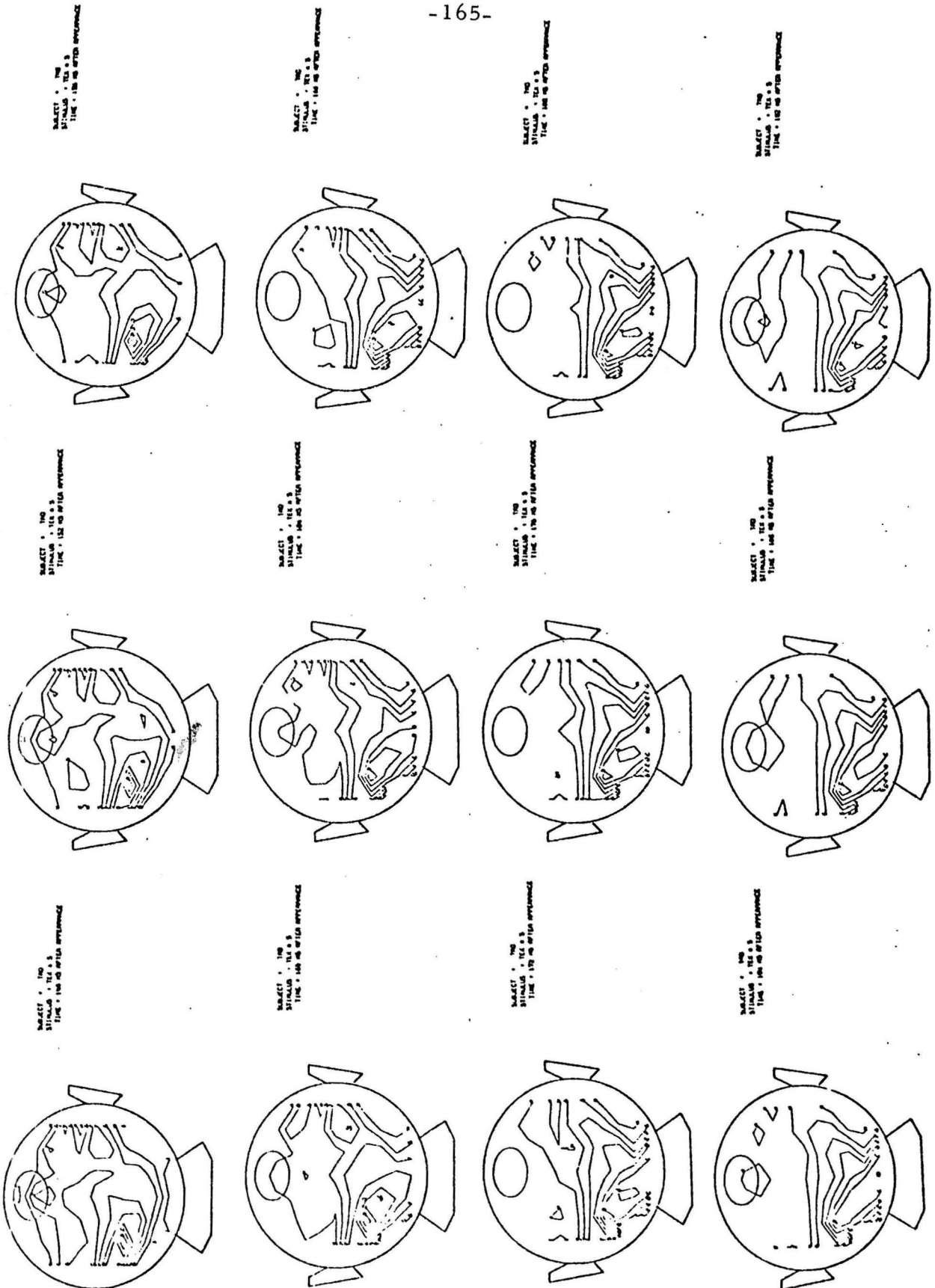


Fig. 5.21 Sub. 1 Tex. 5 148-192 ms after appearance

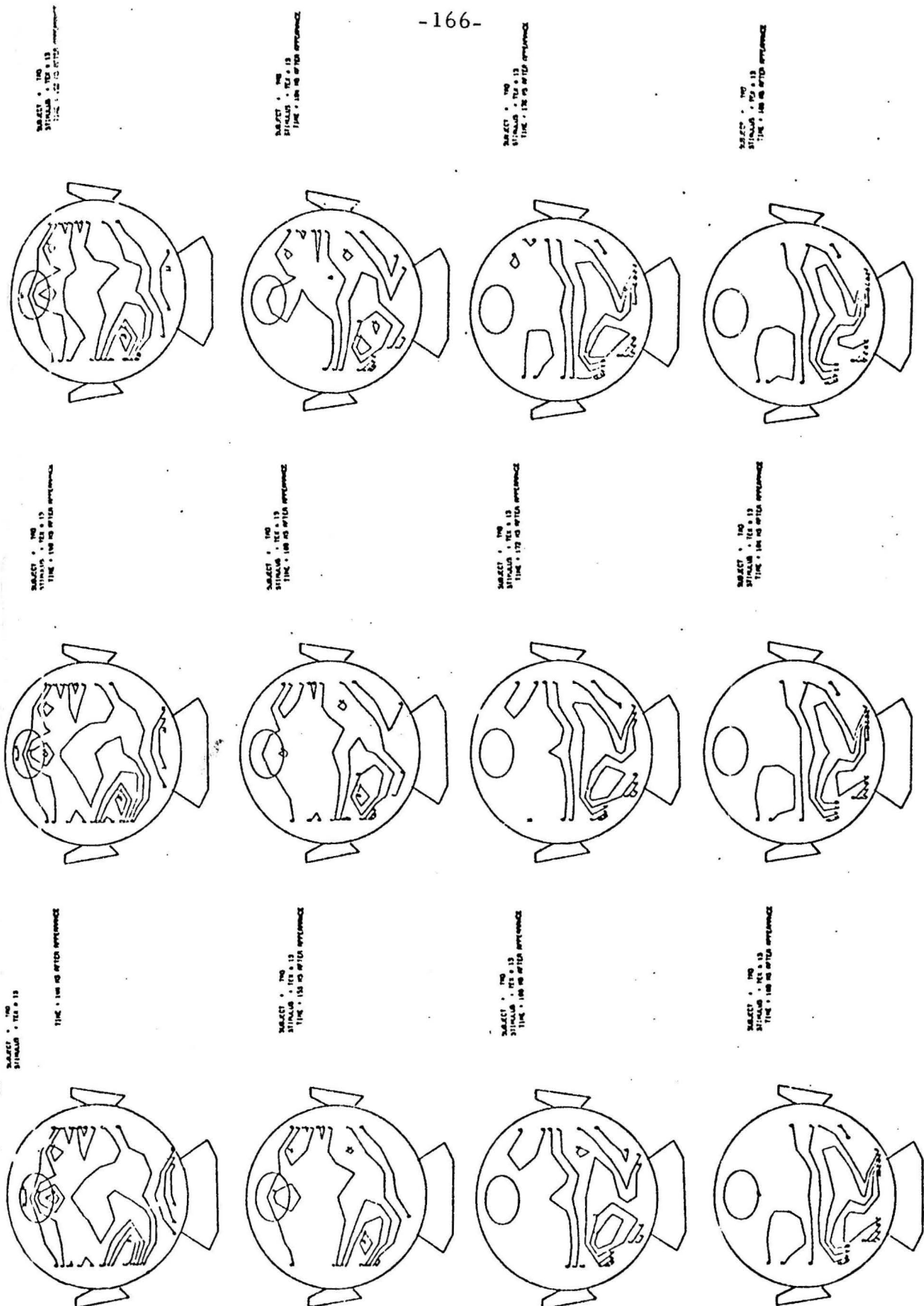


Fig. 5.22 Sub. 1 Tex. 13 144-188 ms after appearance

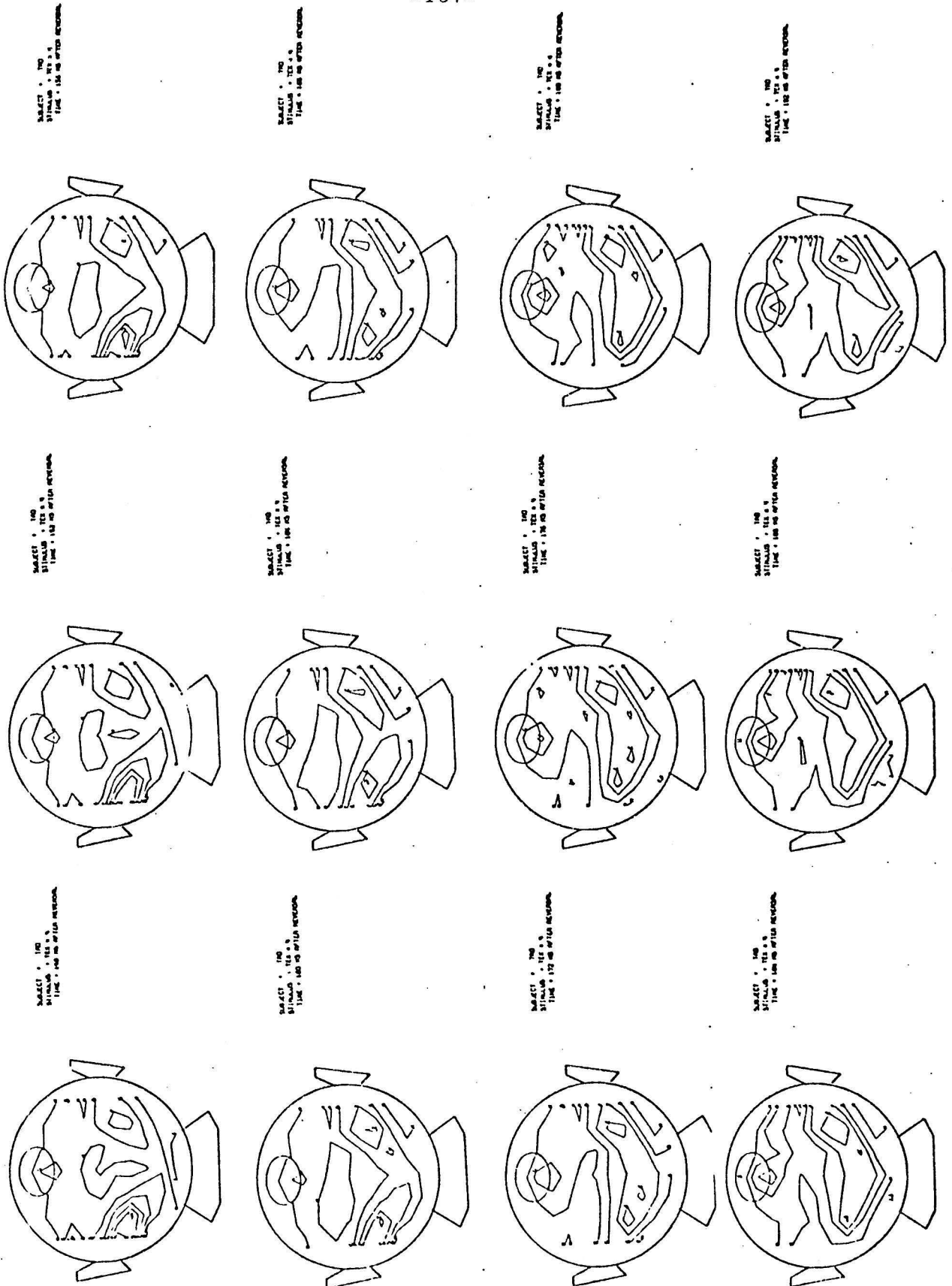


Fig. 5.23 Sub. 1 Tex. 4 148-192 ms after reversal

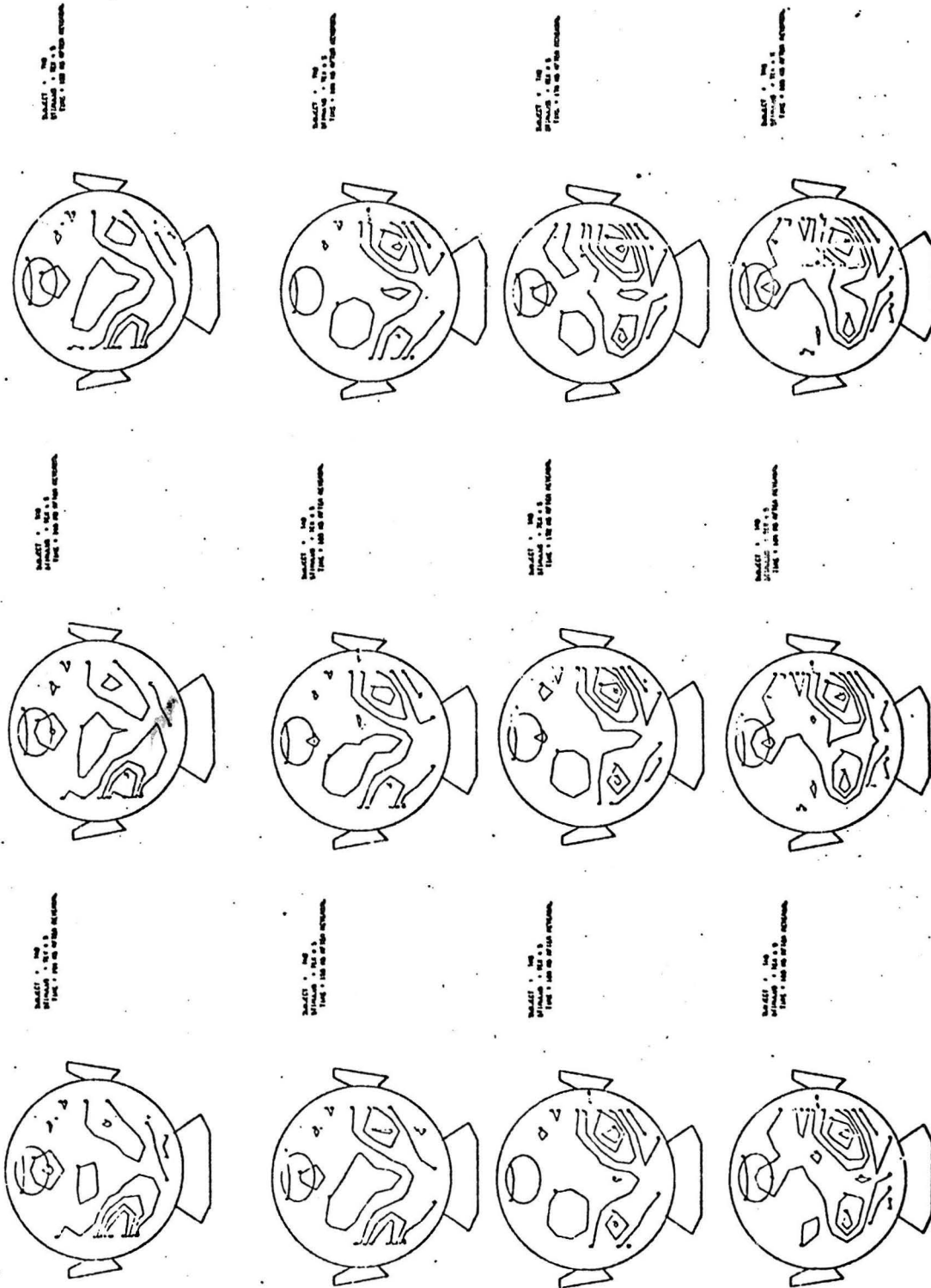


Fig. 5.24 Sub. 1 Tex. 5 144-188 ms after reversal.

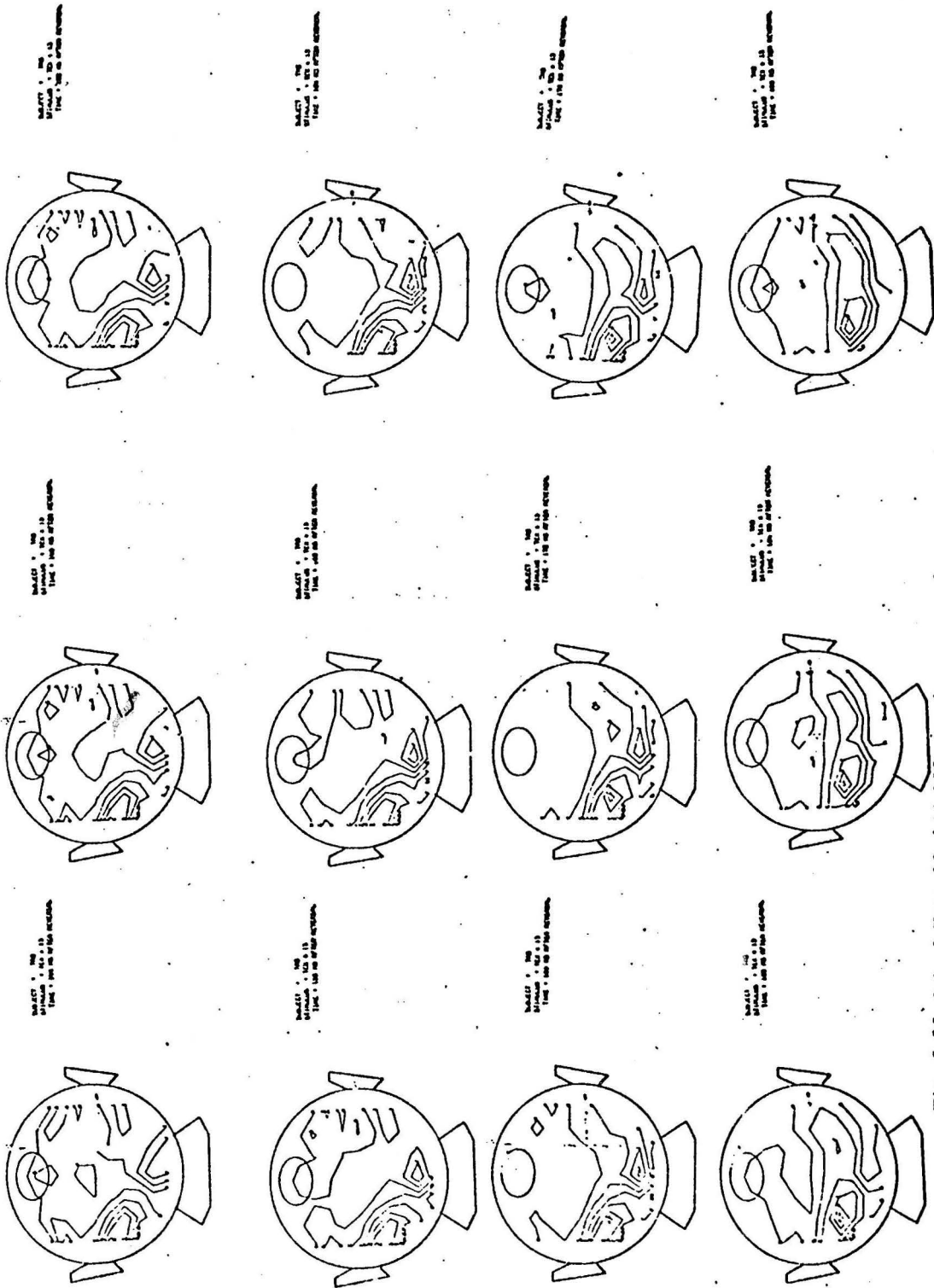


Fig. 5.25 Sub. 1 Tex. 13 144-188 ms after reversal

hidden systematic variations attributable to differences in stimuli.

Of course, the facilities dedicated to the analysis of contour maps for this study are somewhat more specific although no less exhaustive than the various possible statistical tests that might be applied. As explained in Chapter IV, the experimental maps are fit by a localized source model and those parameters of the model that best fit the data are taken as characteristic of the particular response. Having considered theoretical arguments for and against a localization model, the point now is reached where we may explore the capabilities of the model approach using actual data sets. Ultimately, the usage of any analysis technique is largely determined by the overall quality of its results.

Model Sources for Evoked Potential Contours

The conclusions drawn from study of our evoked potential wave-shapes and contour maps have defined certain time periods in the response of all subjects to all stimuli during which scalp electrical activity is quite coherent and concentrated in the occipital region. Sufficient information concerning the active surface locale and the signal strength and polarity is available from the contour maps to allow a reasonable initial guess for the parameters of neuronal current sources capable of generating such contour maps. As described in Chapter IV, an initial guess is needed to 'seed' the iterative optimization algorithm that finds those parameters of our model sources that generate model scalp potentials which best fit the measured data set. In fitting the model-generated potentials to the data, each electrode site is weighted according to the signal-to-noise ratio for the electrode.

As an example of the modeling process, consider the problem of finding the best fitting model potential field for the contour map of subject 3 at a latency of 124 ms following the appearance of texture #1 (shown in Fig. 5.7a). Let us take the simple homogenous sphere model of the head. We first must chose whether to attempt a one-source or a two-source solution. Our catalogue of typical model contour maps is useful for the initial decisions. Fig. 5.26 shows model potential fields for various two-source and one-source parameters. A comparison of the experimental potential fields in Fig. 5.7a with the model fields leads to the suspicion that either a one-source or a two-source solution is possible. Initially, let us try to effect a single-source solution.

Fig. 5.27 shows a front and top view of the optimal single source solution locale within our homogenous model. The horizontal and vertical axes of Fig. 5.27 serve dual roles in the upper and lower left hand quadrants where front view and top view respectively are displayed. The reader should familiarize himself with the display format of Fig. 5.27 so that he can easily distinguish the front and top views of the source locations. The origin of the coordinate system is at the center of the model head; the negative X axis points toward the right ear; the positive Z axis points toward the top of the head; and the positive Y axis points out the back of the head, in the general direction of the inion. The reader may consider himself adept at interpreting these diagrams when he is able to understand that the upper rectangle of Fig. 5.27 is the top view of the source and the lower rectangle is the front view.

CONTOUR RANGE :

K = 209.9927

A = -1.0244

MODEL : HOMOGENEOUS

DIPOLE PARAMETERS :

X = 0.000

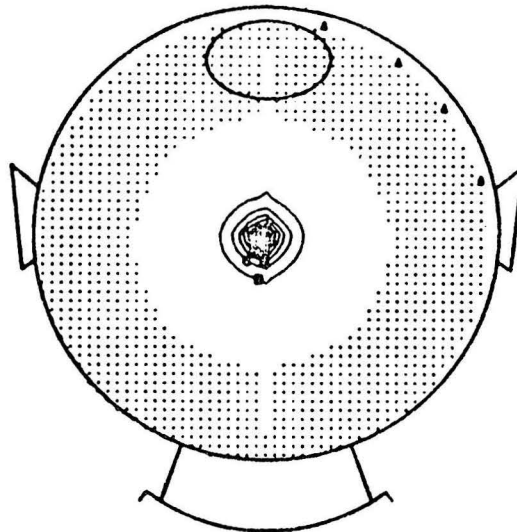
Y = 0.000

Z = 0.900

PX = 0.000

PY = 0.000

PZ = 1.000



(a)

CONTOUR RANGE :

K = 25.5555

A = -1.0280

MODEL : HOMOGENEOUS

DIPOLE PARAMETERS :

X = 0.000

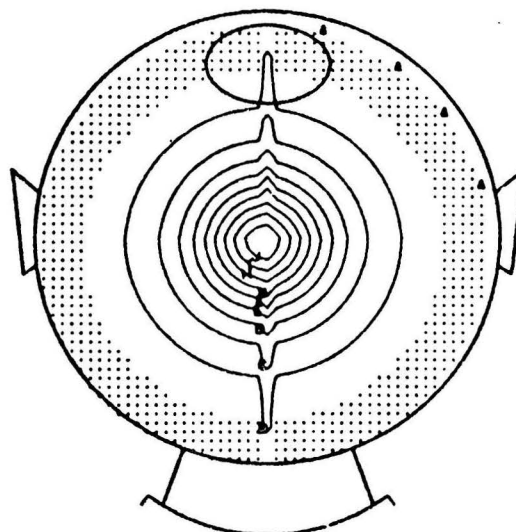
Y = 0.000

Z = 0.700

PX = 0.000

PY = 0.000

PZ = 1.000



(b)

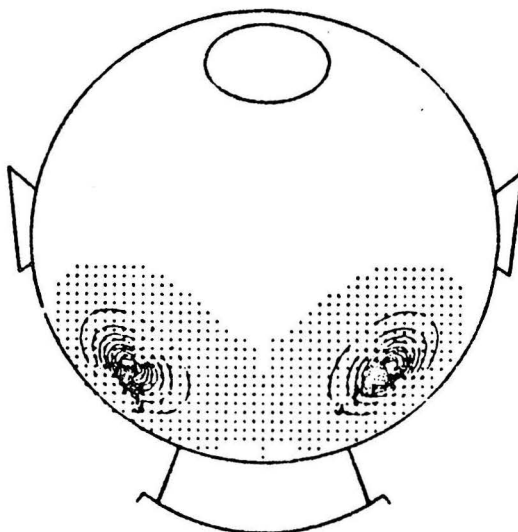
Figure 5.26a Radially oriented dipoles in a homogeneous sphere
(a) $f = 0.90$ (b) $f = 0.70$. Bumps along mid-line are plotting artifact.

CONTOUR RANGE :

K = 2.1772

A = -110.9343

MODEL : HOMOGENEOUS



(a)

DIPOLE PARAMETERS :

X = 0.500

Y = 0.500

Z = 0.500

PX = -0.577

PY = -0.577

PZ = -0.577

X = -0.500

Y = 0.500

Z = 0.500

PX = 0.577

PY = -0.577

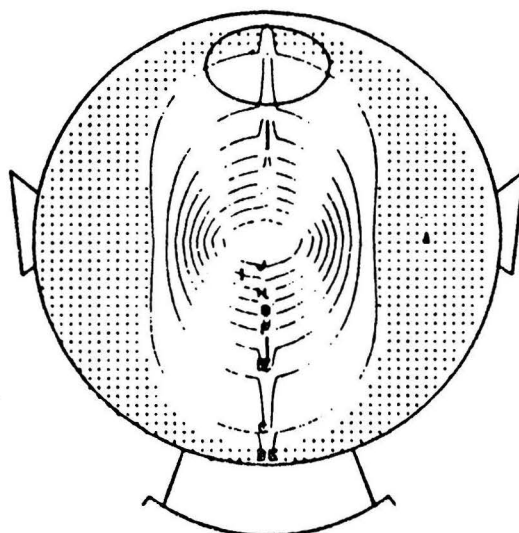
PZ = -0.577

CONTOUR RANGE :

K = 35.2760

A = -3.3748

MODEL : HOMOGENEOUS



(b)

DIPOLE PARAMETERS :

X = 0.200

Y = 0.000

Z = 0.700

PX = -0.707

PY = 0.000

PZ = 0.707

X = -0.200

Y = 0.000

Z = 0.700

PX = 0.707

PY = 0.000

PZ = 0.707

Figure 5.26b Fields from two dipole sources in a homogeneous sphere. (a) Sources easily separable by sight. (b) Combined fields not easily ascribed to one source.

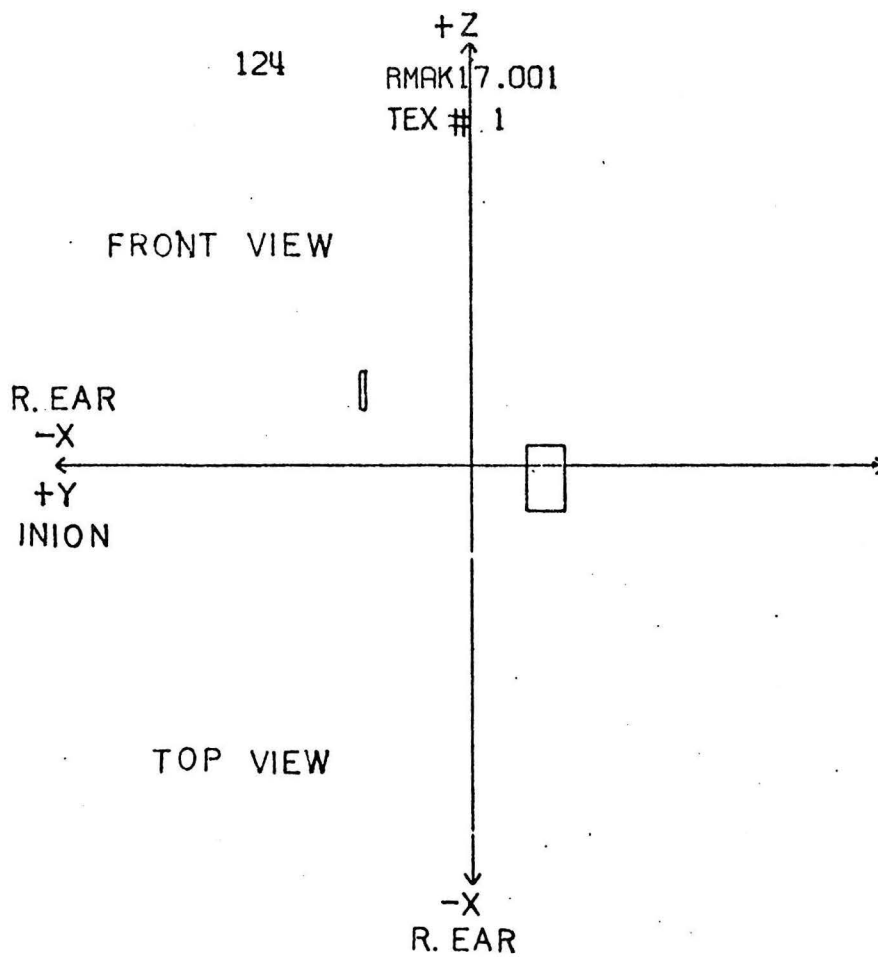


Fig. 5.27 Sub. 3 Tex. 1 Single source solution at 124 ms following appearance

The rectangular regions in Fig. 5.27 are defined by the upper and lower 95% confidence limits on each location parameter. Table 5.5 gives the numerical differences between the actual and optimal field values and the weighted mean sum of squares (PHI) of those differences. While the fit achieved by the single source model to the test data is reasonable, the final location for the model source leaves us somewhat uncomfortable since it is nearly in the center of our model head. Hence, we now consider a two-source model.

As seen in Fig. 5.26, the field of two relatively close sources in our model is quite similar to a single-source field and also makes a reasonable initial guess for our actual data field. Using two-source parameters for our new initial guess, the optimization routine obtains the model locales shown in Fig. 5.28. Table 5.6 gives the error differences corresponding to the two-source solution. It is interesting to note the correspondence of the actual test field, the single-source model field and the double source model field (shown in Fig. 5.29). The two-source model field is nearly indistinguishable from the actual data field.

The locations obtained for the two source solution have approximately the same size 95% confidence limits as the single source locations. The overall weighted sum of squares of error differences for the two source solution is comparable to the single source result. The actual locale of the two sources in the model head has more eccentricity and thus, is more attractive than the very central single source solution.

Time Course of the Source Solution

Having obtained a reasonably good characterization of one sample

N = 22 K = 6 IP = 0 M = 2						
FF = 0.237E 01 I = 0.203E 01 E = 0.500E-04 TAU = 0.100E-02						
PARAMETERS -0.12157898E 01 -0.54640512E 01 -C.11836414E 01 0.19819355E 01 0.68005371E 00						
0.29528791E 00						
X(I,1) Y OBS. Y PRED. DIFF						
0.53417249E 00	0.51289997E 01	0.45415897E 01	0.58740997E 00			
0.70979875E 00	-0.15563992E 01	0.27663517E 00	-0.18336344E 01			
0.56589232E 00	-0.32709999E 01	-0.49562733E 01	0.16952734E 01			
0.51710520E 00	-0.59139932E 01	-0.61877947E 01	0.37379551E 00			
0.17453361E 00	-0.13429935E 01	-0.26435747E 01	0.13005753E 01			
0.13099885E 00	0.20000000E 01	0.11652098E 01	0.83479023E 00			
0.10980148E 01	-0.19370327E 02	-0.19533081E 02	0.16209412E 00			
0.10484419E 01	0.35289933E 01	0.32311630E 01	0.29783630E 00			
0.56589282E 00	-0.95853935E 01	-0.88202753E 01	-0.76572418E 00			
0.10980158E 01	-0.14956999E 02	-0.14678744E 02	-0.17825508E 00			
0.47996613E 00	-0.58999996E 01	-0.71437645E 01	0.12437649E 01			
0.74176389E 00	0.64629998E 01	0.69398499E 01	-0.49685001E 00			
0.10622129E 01	0.24709997E 01	0.22244091E 01	0.24659061E 00			
0.70979006E 00	-0.50000000E 01	-0.44170675E 01	-0.58293247E 00			
0.10494251E 01	0.19709997E 01	0.18319139E 01	0.13908577E 00			
0.10557148E 01	-0.77570000E 01	-0.80304308E 01	0.27343082E 00			
0.10908308E 01	-0.17185939E 02	-0.17286346E 02	0.10035706E 00			
0.78539850E 00	-0.13629000E 02	-0.12207665E 02	-0.14213343E 01			
0.53417462E 00	0.31429996E 01	0.39468451E 01	-0.80384541E 00			
0.10657139E 01	-0.17852993E 01	0.13813210E 00	-0.19241314E 01			
0.10622110E 01	0.50859995E 01	0.45725203E 01	0.51347923E 00			
0.10484428E 01	-0.13289995E 01	-0.74189091E 00	-0.58710861E 00			
PHI S F LAMBDA ANALYTIC PARTIALS USED						
0.27171698E 01	0.41209602E 00	0.100E-03				

Table 5.5 Numerical differences at each electrode site for the best fit solution of Fig. 5.27

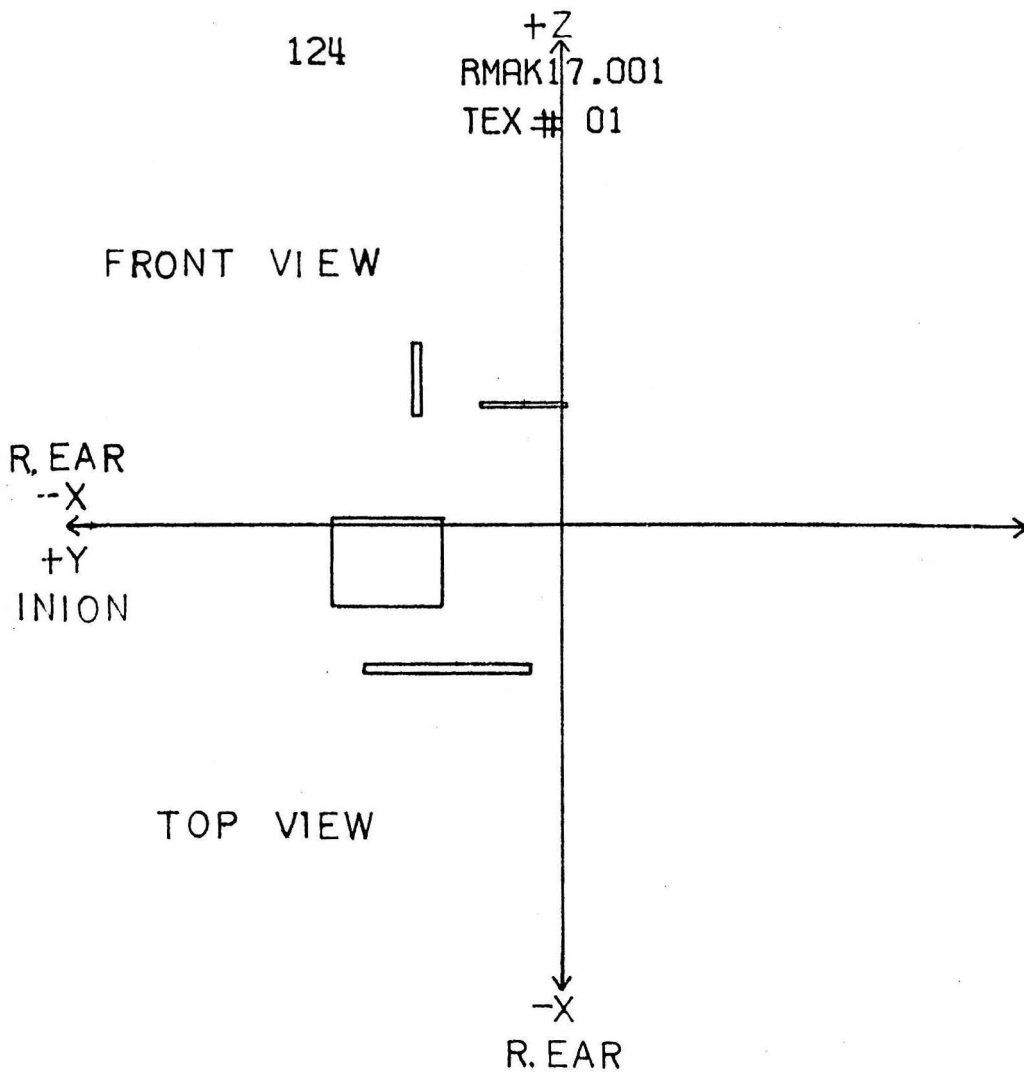
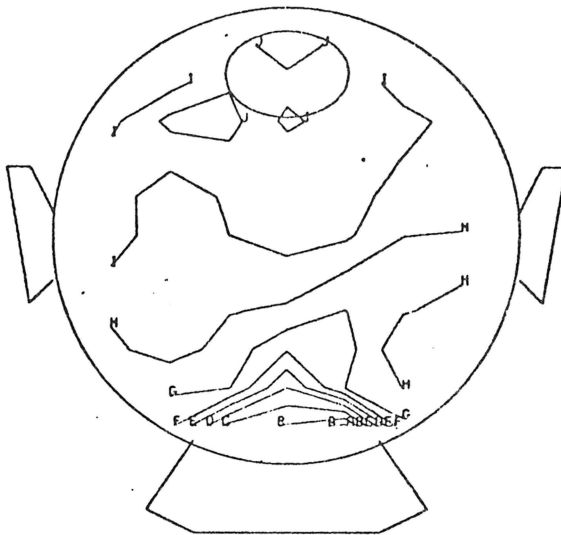


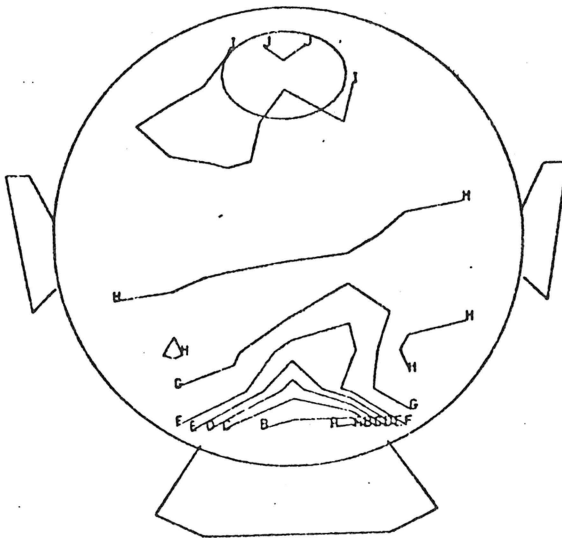
Fig. 5.28 Sub. 3 Tex. 1 2 sources 124 ms after appearance

N = 22 K = 12 IP = 0 V = 2 FF = 0.209E 01 T = 0.204E 01 E = 0.503E-04 TAU = 0.100E-02									
PARAMETERS									
	-0.17926474E 01	-0.13429489E 01	0.14072657E 01	0.72417080E 00	0.38618099E-01				
	0.48298693E 00	0.78901142E 00	-0.20549355E 01	-0.22234373E 01	0.27127236E 00				
	-0.40300184E 00	0.31214786E 00							
X(I,1) Y OBS. Y PRED. DIFF									
0.53417248E 00	0.51289997E 01	0.49424715E 01	0.18552780E 00						
0.70878875E 00	-0.15569992E 01	-0.1091799E 01	-0.34781933E 00						
0.56589282E 00	-0.32709999E 01	-0.39289465E 01	0.65794659E 00						
0.91710520E 00	-0.50139992E 01	-0.62628593E 01	0.4486017E 00						
0.17453361E 00	-0.13429995E 01	-0.14001350E 01	0.57135582E-01						
0.13089889E 00	0.20000000E 01	0.17721272E 01	0.22787285E 00						
0.10980148E 01	-0.19370987E 02	-0.19237708E 02	-0.3279419E-01						
0.10484419E 01	0.35289993E 01	0.26093111E 01	0.91968822E 00						
0.56589282E 00	-0.93039995E 01	-0.94271033E 01	-0.14889622E 00						
0.10980158E 01	-0.14056999E 02	-0.14296872E 02	-0.56012726E 00						
0.47956610E 00	-0.50999996E 01	-0.56273661E 01	-0.27263355E 00						
0.74176385E 00	0.64429998E 01	0.70105425E 01	-0.56754303E 00						
0.10622129E 01	0.24709997E 01	0.40192890E 00	0.20690708E 01						
0.70879076E 00	-0.50000000E 01	-0.46405754E 01	-0.35942459E 00						
0.10494251E 01	0.19709997E 01	0.87464615E 00	0.10963535E 01						
0.10657148E 01	-0.77570000E 01	-0.65306478E 01	-0.12505322E 01						
0.10508308E 01	-0.17185985E 02	-0.17370255E 02	0.18426514E 00						
0.78539860E 00	-0.15029000E 02	-0.13117239E 02	-0.51176071E 00						
0.53417462E 00	0.31429996E 01	0.38908491E 01	-0.74784946E 00						
0.10657139E 01	-0.17859993E 01	-0.96479416E 00	-0.82120514E 00						
0.10622110E 01	0.50055995E 01	0.43604708E 01	0.72552872E 00						
0.10484428E 01	-0.13289995E 01	-0.16372495E 01	0.30825043E 00						
PHI S E LAMBDA ANALYTIC PARTIALS USED 0.14602489E 01 0.38213205E 00 0.100E 00									

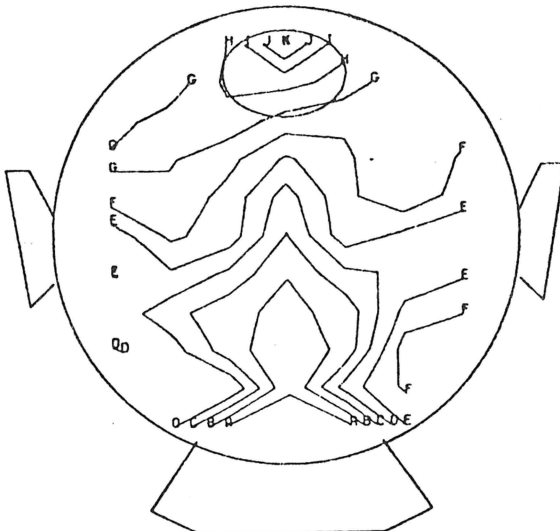
Table 5.6 Numerical differences for the solution of Fig. 5.28



SUBJECT • TEST
STIMULUS • 2 DIPOLE
TIME • 124 MS AFTER APPEARANCE



SUBJECT • A.J.K
STIMULUS • TEX # 1
TIME • 124 MS AFTER APPEARANCE



SUBJECT • TEST
STIMULUS • 1 DIPOLE
TIME • 124 MS AFTER APPEARANCE

Fig. 5.29 Sub. 3 Tex. 1 124 ms after appearance and test models

time using our two source model, the next step in our analysis is to proceed backward and forward through the sample times solving for the best two-source fit and using the solution at each time as the initial guess for the next time. Our criterion for a good solution is the extent of the 95% confidence limit boundaries about the solution locations. When the confidence limits undergo substantial increase compared to the previous ones we know the coherency of the data has been substantially reduced.

Fig. 5.30a shows a sequence of location solutions for the subject 3 data set over the range of 116-136 ms following the appearance of texture #1. The localizations in this time span of 20 ms are quite good and the motion of the sources is apparent. The times shown in Fig. 5.30a represent the peak of the appearance response. Now since our goal in all this analysis is not only to obtain good modelings of our data sets but more important to learn how sensitive our models are to statistical variations in the texture stimuli, let us examine the same six sample times of subject 3's response to appearance of Textures 2, 7, and 6, shown in Fig. 5.30 b-d. Careful inspection of the solution of each texture shows no outstanding differences among them. The general behavior of the two model sources goes as follows. From an initial configuration quite close together to the right of the midline, the sources move in toward the midline dipping slightly but then rising as they reach their final position. With some variations in absolute positions and confidence limits, the just described behavior is typical for each stimulus shown to subject 3 over the time period covering the peak response.

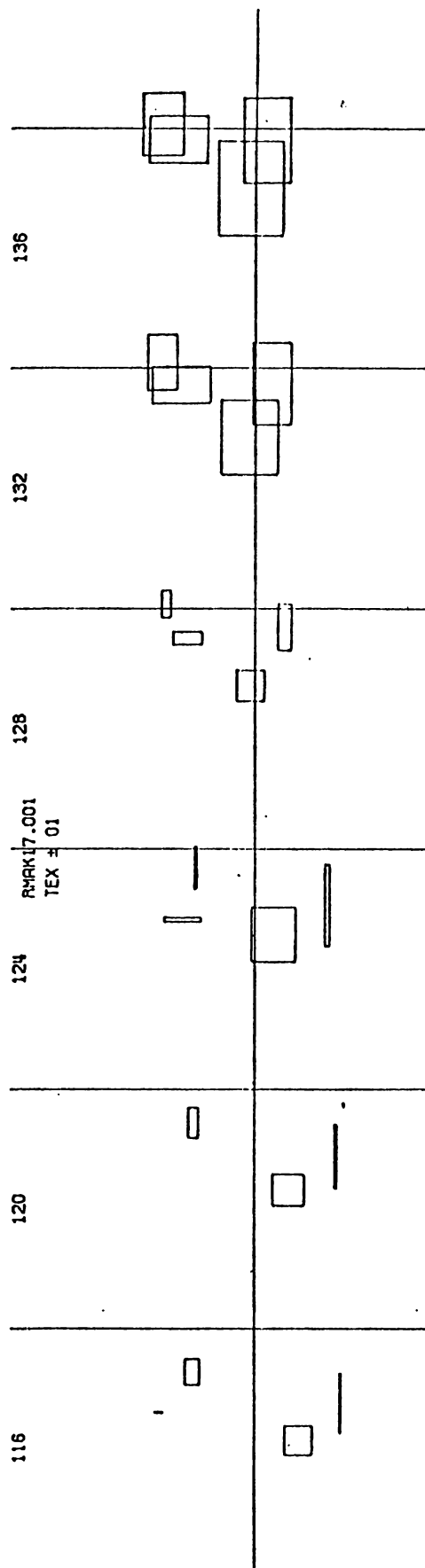


Fig. 5.30a Sub. 3 Tex. 1 2 sources 116-136 ms after appearance

-181-

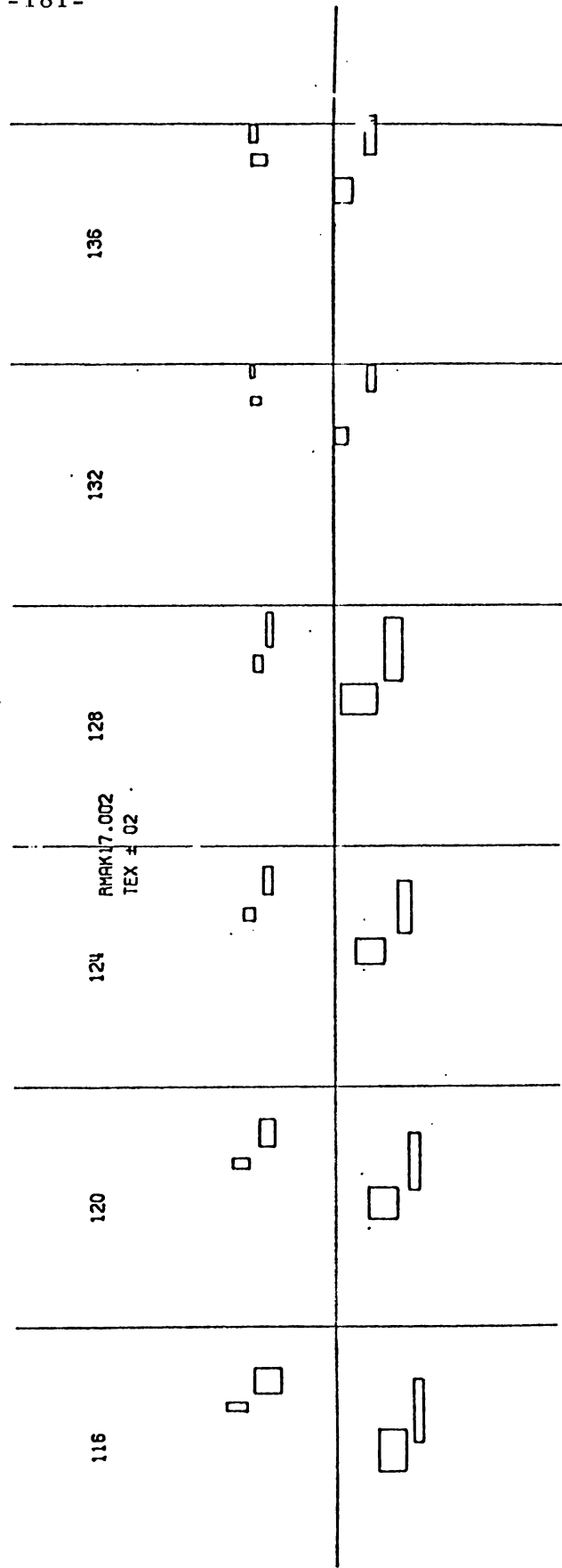


Fig. 5.30b Sub. 3 Tex. 2 2 sources 116-136 ms after appearance

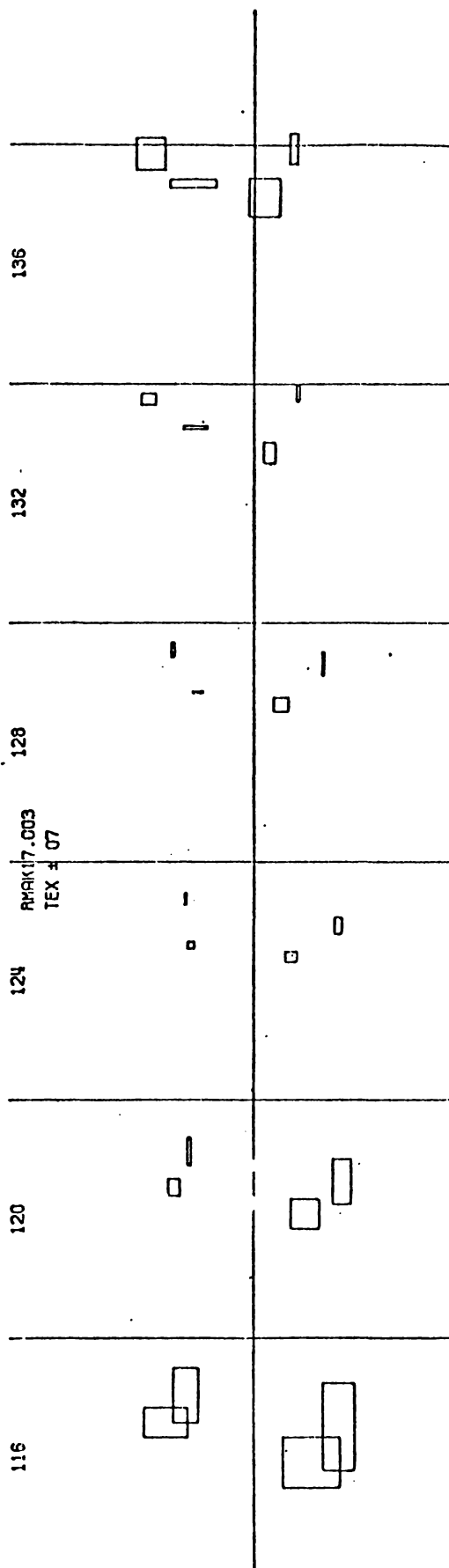


Fig. 5.30c Sub. 3 Tex. 7 2 sources 116-136 ms after appearance

-182-

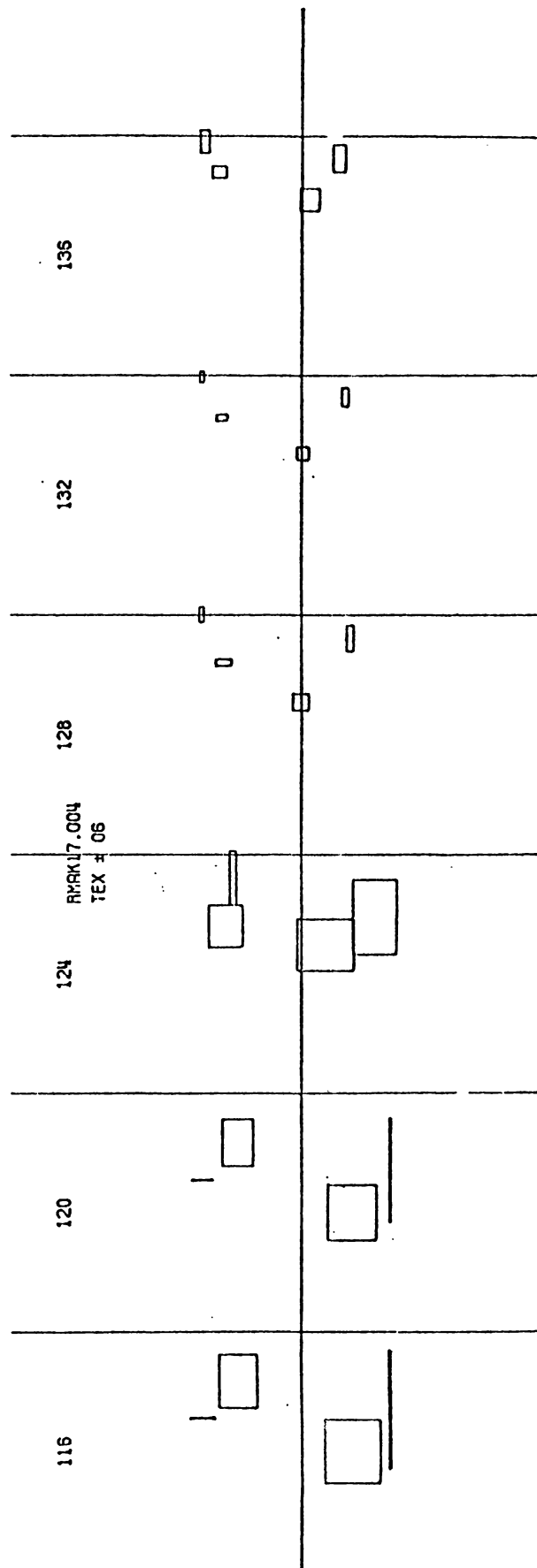


Fig. 5.30d Sub. 3 Tex. 6 2 sources 116-136 ms after appearance

Next we consider subject 3's response to pattern reversal stimuli. Because of the very symmetric nature of the first peaks following appearance and reversal, the same sample times were analyzed for both. Figs. 5.31-5.34 show best fit solutions for pattern reversal of textures 1, 2, 7 and 6 at 116-136 ms latency. While the reversal solutions occupy the same general area as the appearance sources, the time course of their activity is in striking contrast. Moreover, the solutions for pattern reversal response are uniquely linked to each particular pattern stimuli. Fig. 5.35 gives a schematic representation of the behavior of the two-source solutions for each of the four textures shown to subject 3.

As seen in Fig. 5.35, there are numerous differences in starting positions, locus of motion, and final position among the solutions for the four stimuli. There seems to be a basic difference between the solutions for textures #1 and #2 and the solutions for #7 and #6. The sources for both textures #1 and #2 start out close together and move apart, while those for textures #7 and #6 begin apart and move together. Within the two groupings just made, the differences between members seems to involve a sort of orthogonal rotation. For texture #1 the two sources move backward and forward respectively while for #2 they move down and up respectively. Likewise, for the solutions in which sources converge, the two generators move either forward and backward (texture #7) or down and up (texture #6). The differences in source solutions just described are significant at the 95% confidence level and represent variations in the amplitude and phase relationships of the

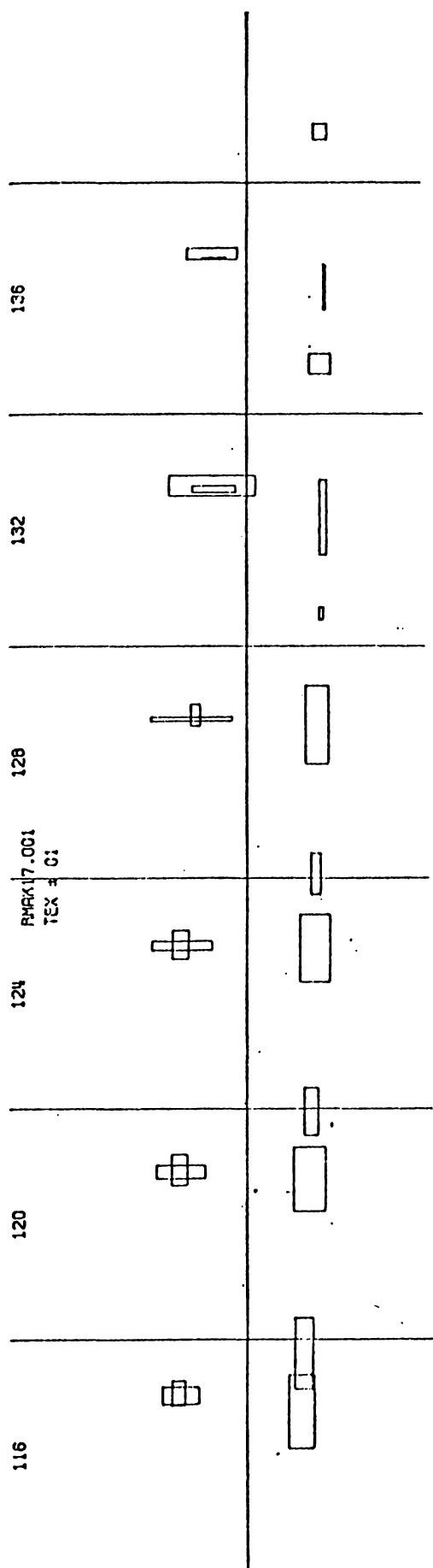


Fig. 5.31 Sub. 3 Tex. 1 2 sources 116-136 ms after reversal

-184-

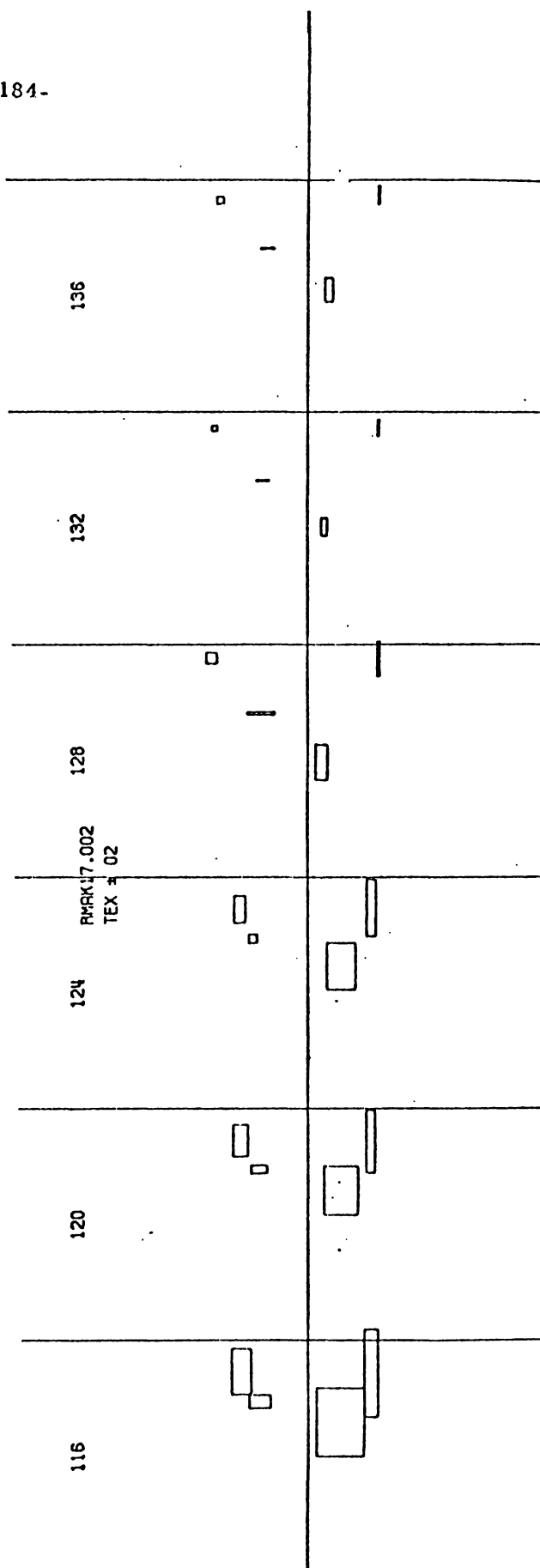


Fig. 5.32 Sub. 3 Tex. 2 2 sources 116-136 ms after reversal

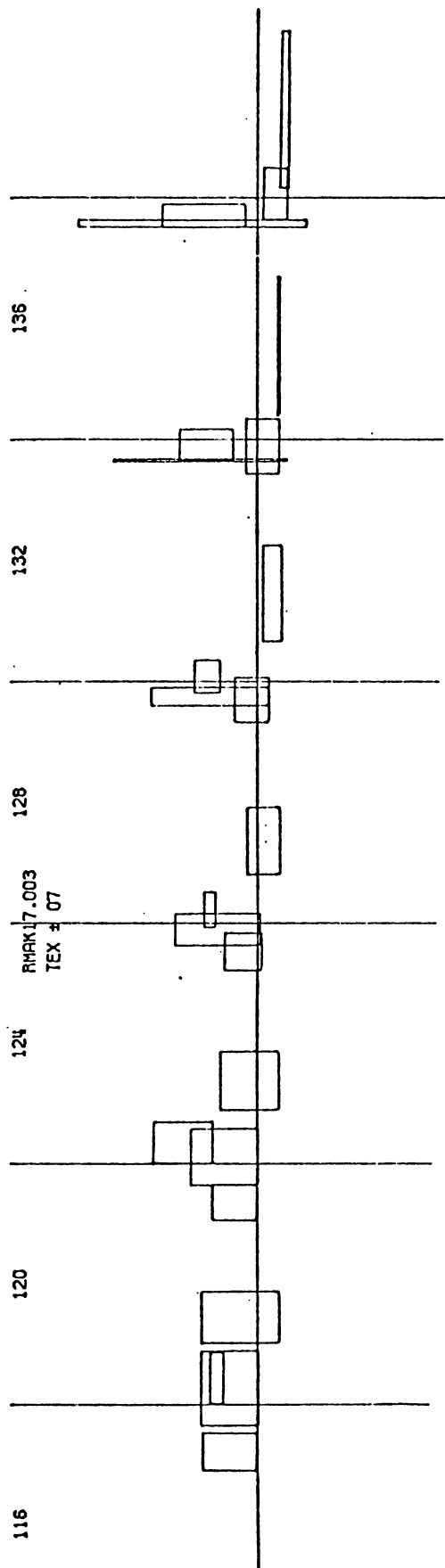


Fig. 5.33 Sub. 3 Tex. 7 2 sources 116-136 ms after reversal

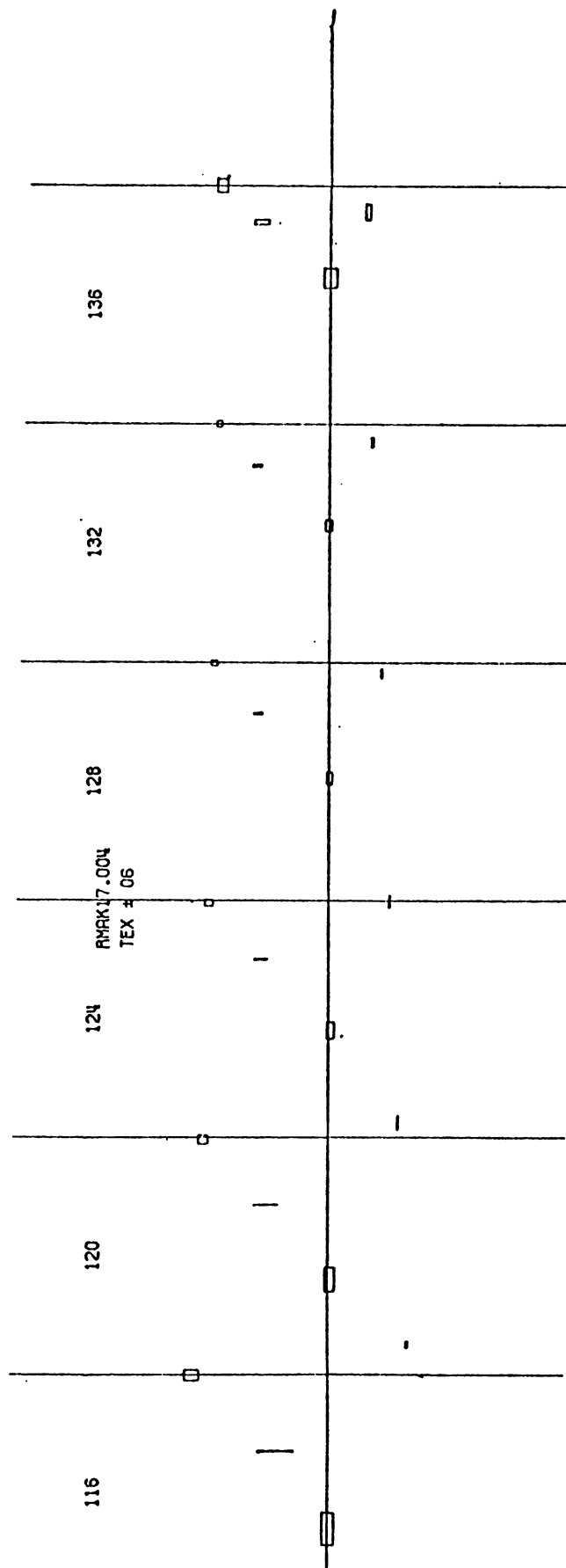


Fig. 5.34 Sub. 3 Tex. 6 2 sources 116-136 ms after reversal

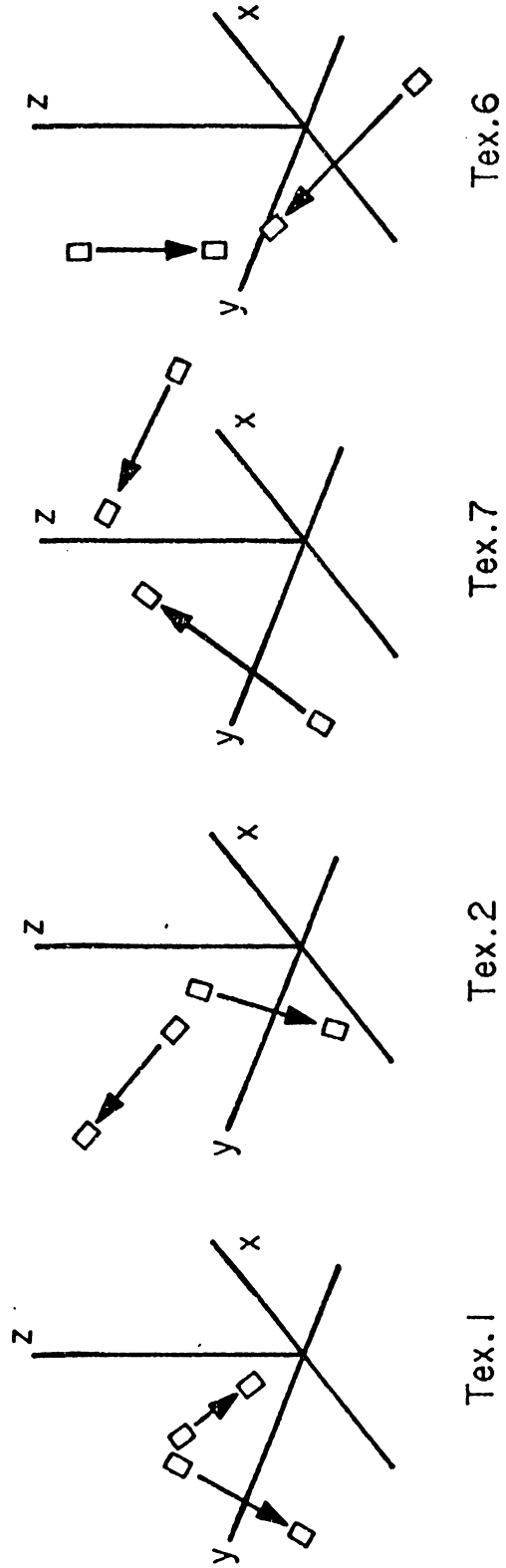


Fig. 5.35 Two source solution; sub. 3, 116-136 ms after reversal (tex. #1. #2, #7, #6).

signals and the signal-to-noise ratios on each electrode in the recording array.

To determine whether or not the activity pattern for a given texture may duplicate that for a different one at some earlier or later time than those just analyzed, extended series of two source solutions were made for some of the subject 3 stimuli. Figs. 5.36 - 5.38 show an extended set of two source solutions for textures 1, 2, and 7. In general, the solutions much outside the 20 ms peak region tend to have appreciably larger confidence limits and hence are somewhat less reliable than the 116-136 ms region solutions. The texture #1 solutions simply maintain their nominal positions outside the peak time period while their 95% confidence boundaries grow by factors upwards of 2x - 4x. Expansion of boundaries is also characteristic of the texture #7 solutions which also have larger boundaries than the other stimuli solutions in the peak response region. The texture #2 solutions are reasonably good outside the peak response period. Texture #2 locations follow their initial tendency of divergence as time increases up to 164 ms latency. As time decreases, the texture #2 sources show some divergence in certain axes but this behavior is still different from that of the other stimuli solutions. Hence we can confidently state that the two source modeling analysis has precisely quantitized subtle differences in the evoked potentials for our different texture stimuli.

We now extend our analysis to the data sets of the remaining 2 subjects. Here we seek solutions during the occurrence of the primary negative-going peak following appearance and reversal events. We can

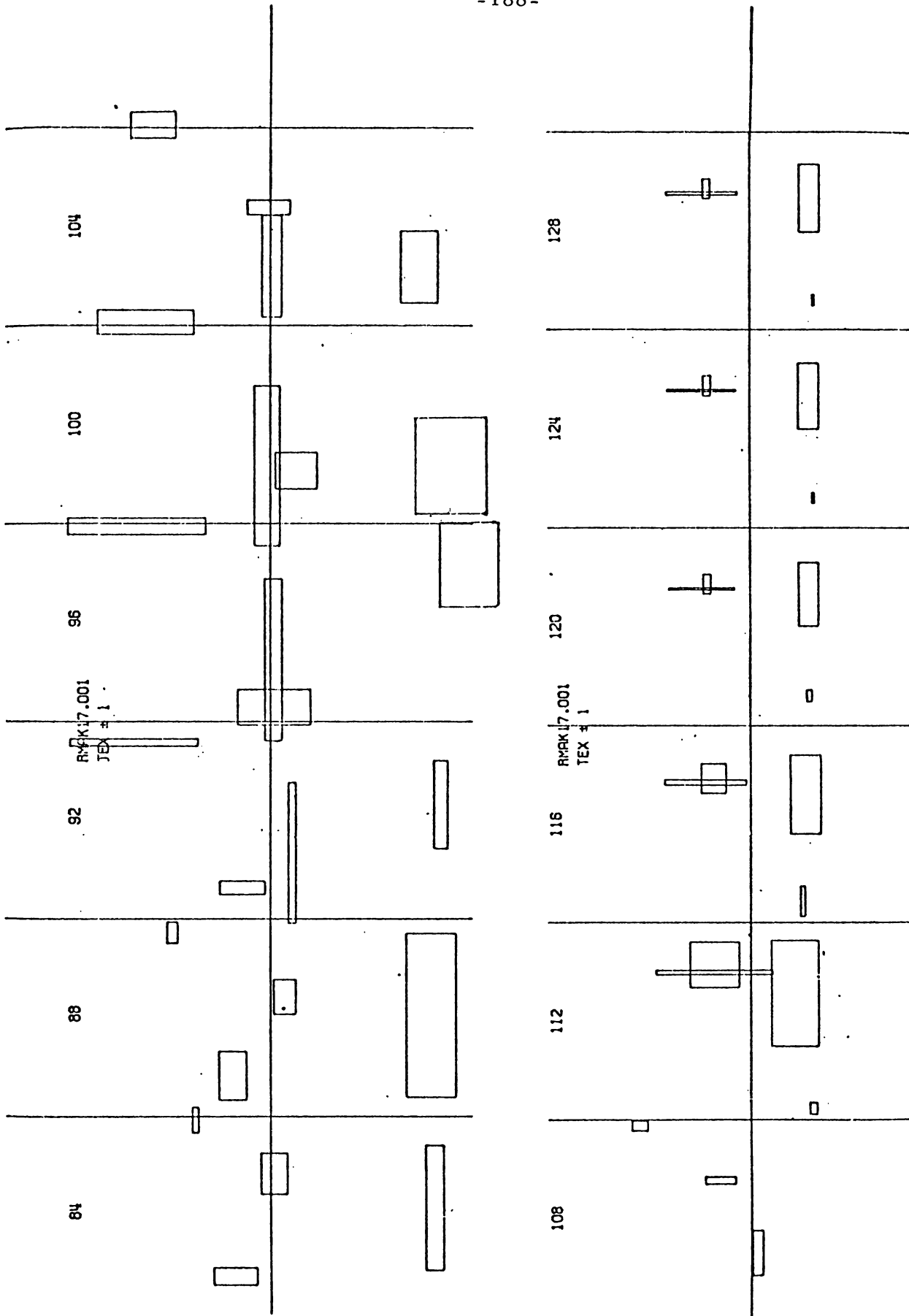


Fig. 5.36a Sub. 3 Tex. 1 2 sources 84-128 ms after reversal

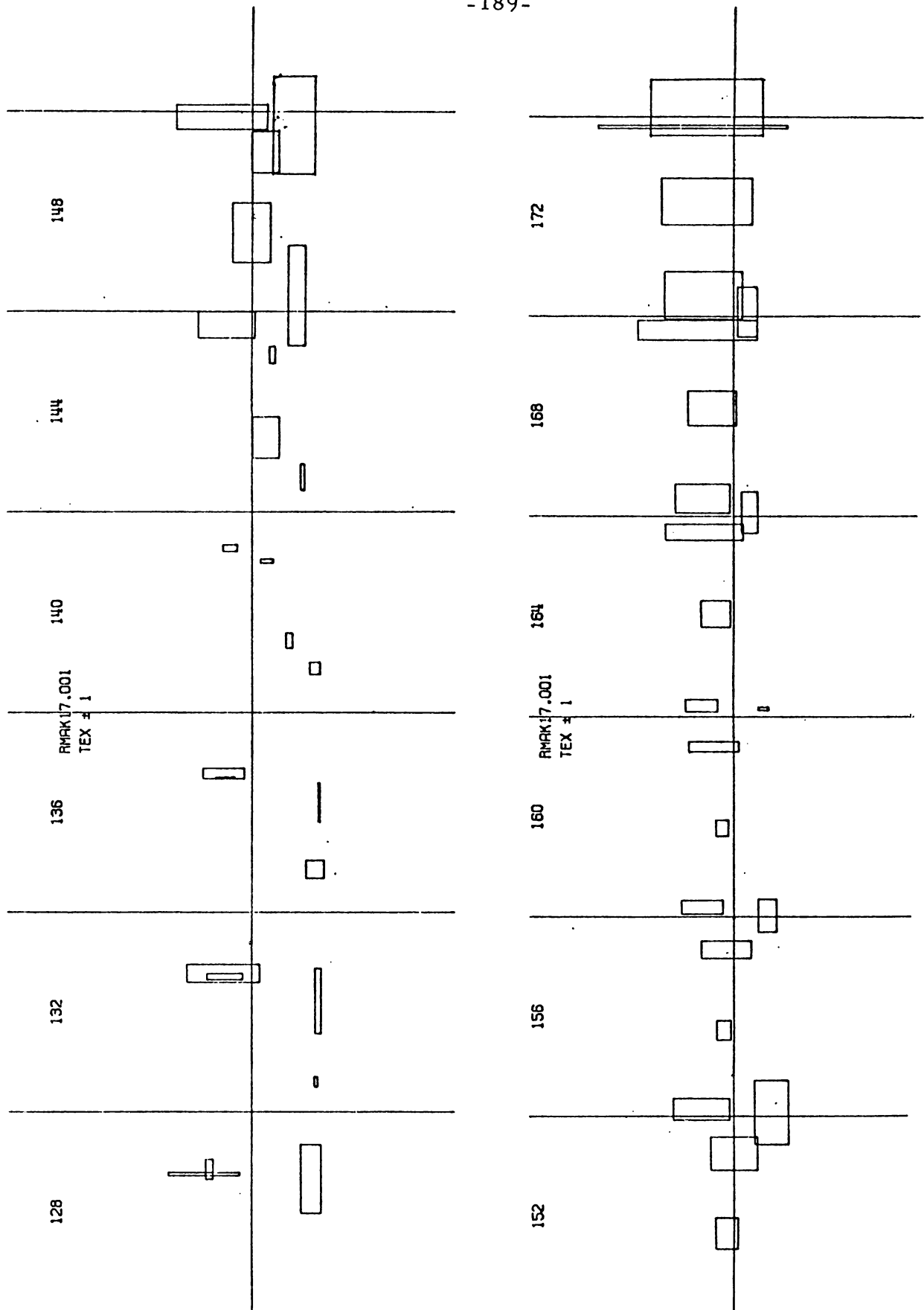


Fig. 5.36b Sub. 3 Tex. 1 2 sources 128-172 ms after reversal

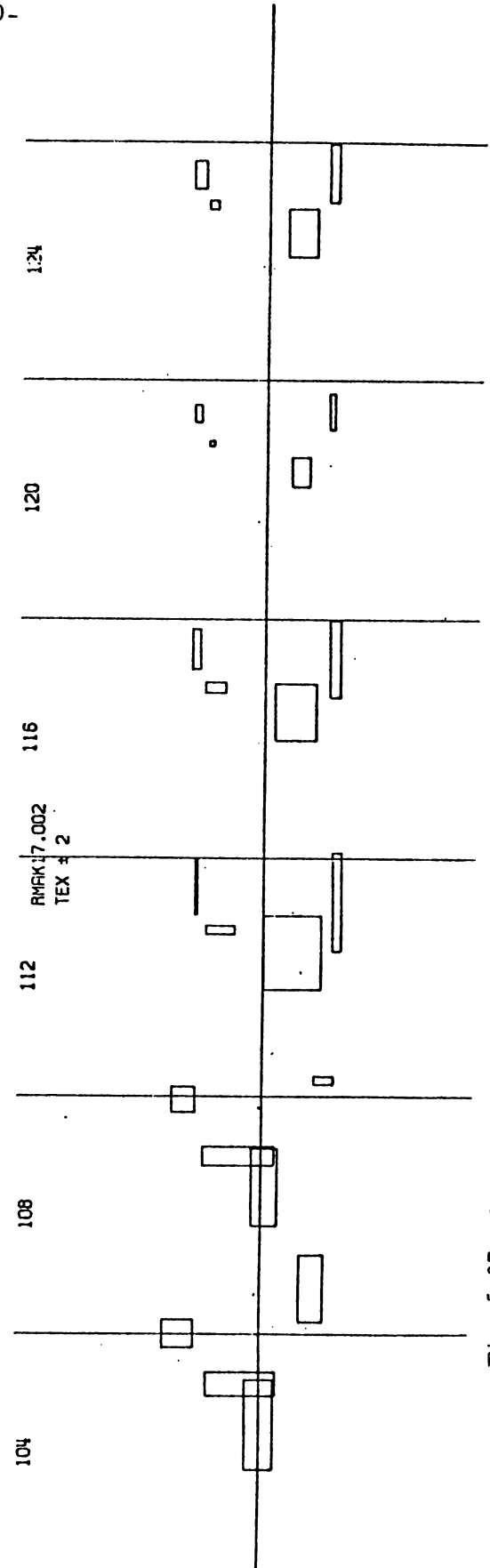
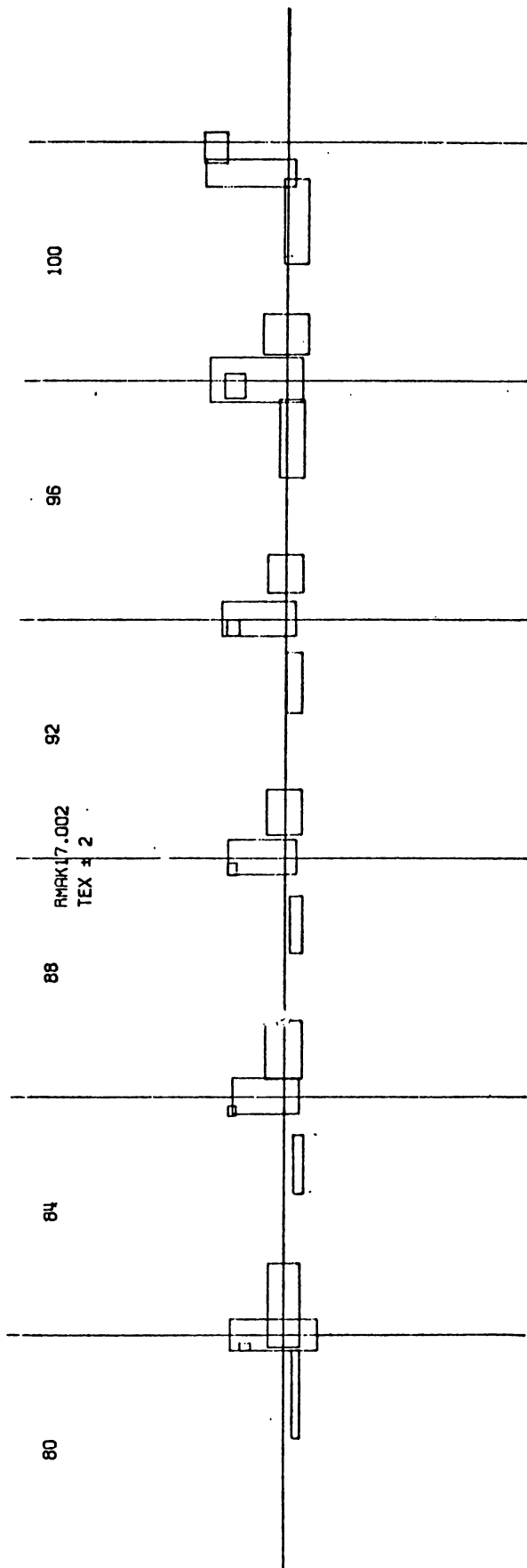


Fig. 5.37a Sub. 3 Tex. 2 2 sources 80-124 ms after reversal

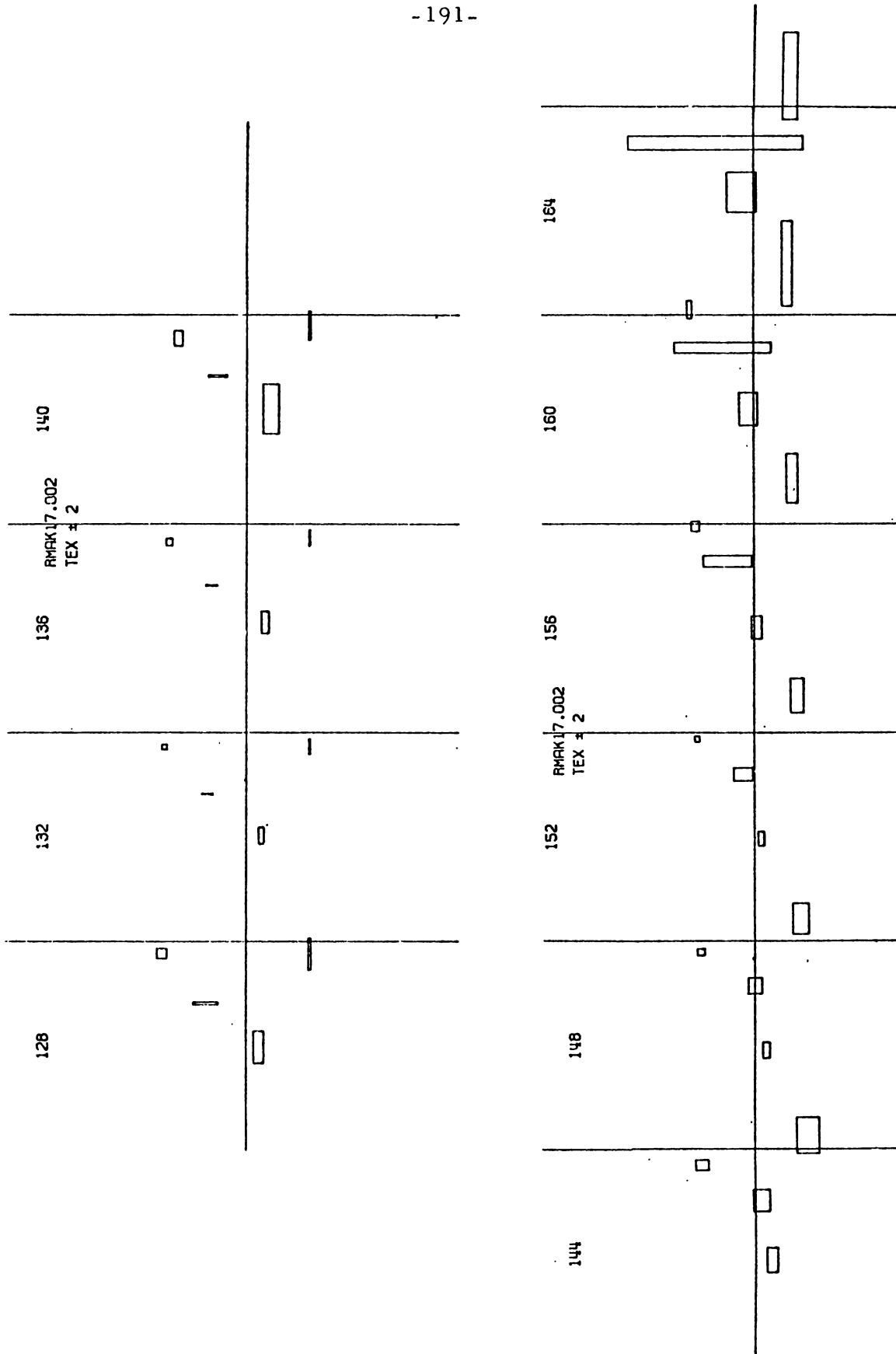


Fig. 5.37b Sub. 3 Tex. 2 2 sources 128-164 ms after reversal

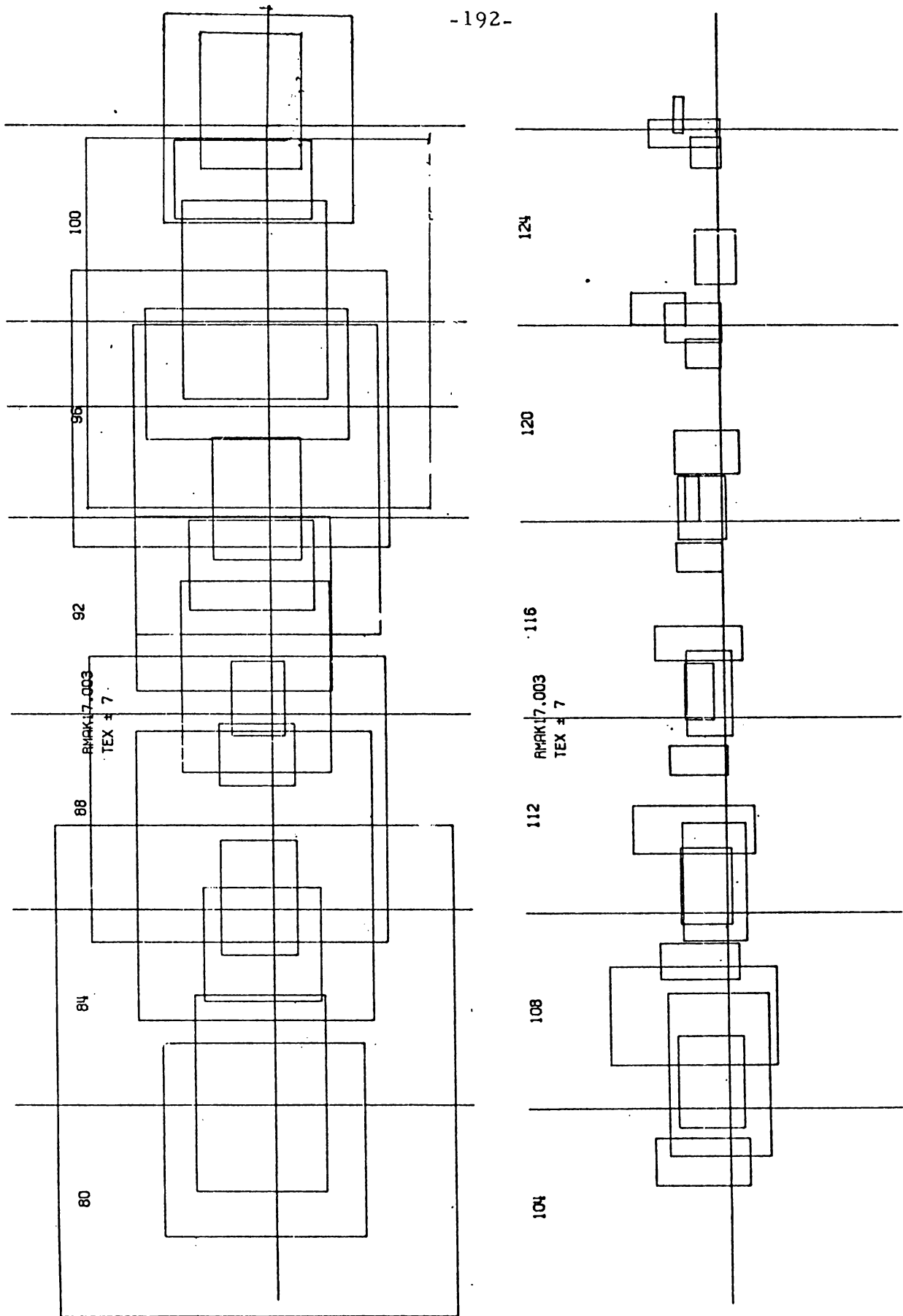


Fig. 5. 38a Sub. 3 Tex. 7 2 sources 80-124 ms after reversal

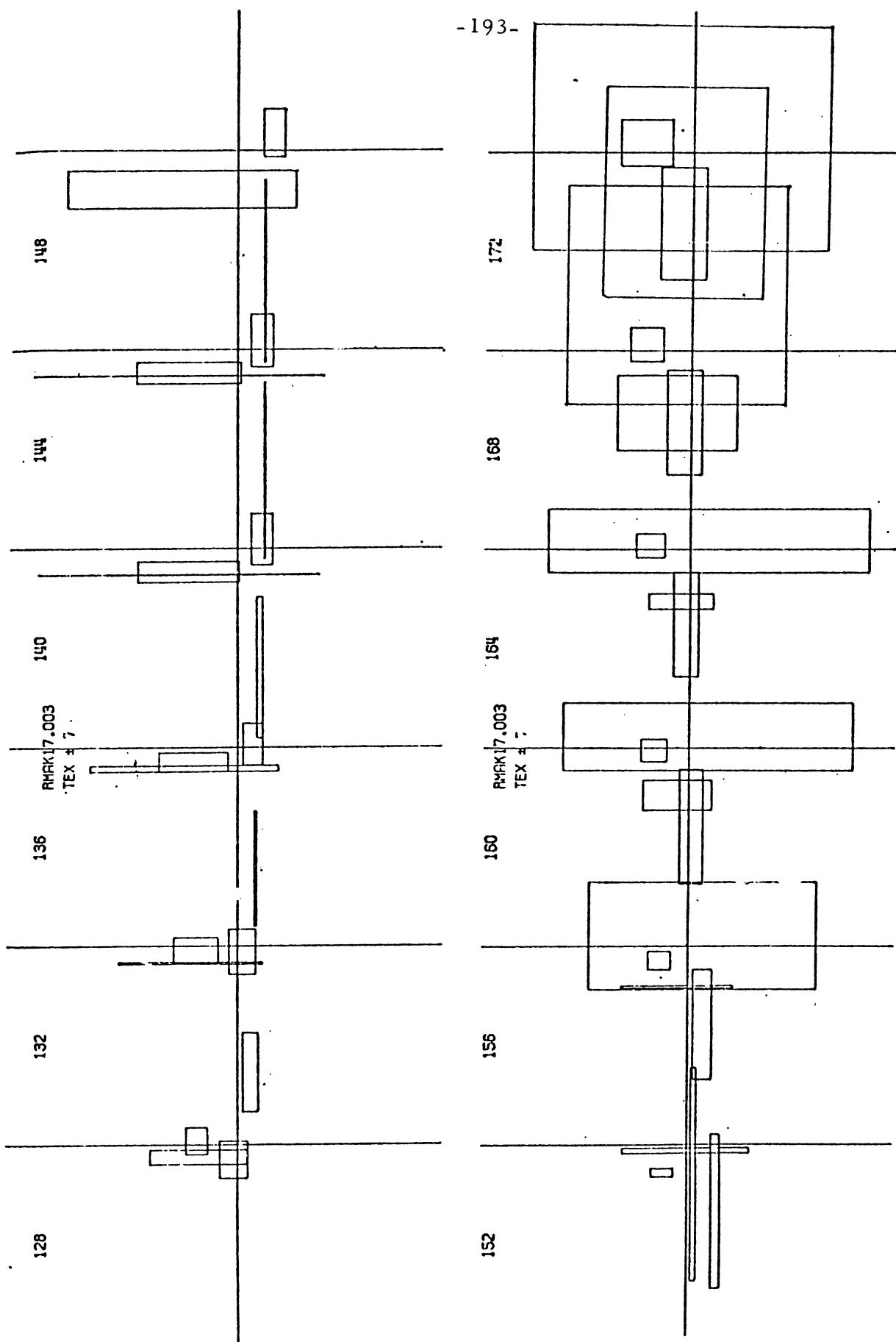


Fig. 5.38b Sub. 3 Tex. 7 2 sources 128-172 ms after reversal

at least expect to obtain good solutions with tightly delineated confidence boundaries during these peaks.

The data set for subject 2 presents an immediate variation from our previous results: 'good' solutions can only be obtained via a single-source model. The solutions for a two-source model of the subject 2 data simply refuses to converge to reasonable confidence boundaries. As shown in Fig. 5.39, the two source solutions generally encompass most of the volume of the model head and beyond within their 95% confidence regions.

The single-source analysis of subject 2 data yields quite acceptable solutions for the 3 stimuli shown to this subject and our interpretation centers on these. The appearance solutions shown in Fig. 5.40-5.42 for textures #7, #8 and #6 contain significant differences at the 95% confidence level. The source for texture #7 converges toward the center of our model head as its confidence boundaries tighten during the 176-220 latency period. Neither the texture #8 nor the texture #6 solutions, Fig. 5.41 and Fig. 5.42, localize at the center of the model. The solution for texture #8 is found quite far off center in the model head where it stays for the entire 44 ms period under consideration. The texture #6 solution is found at quite the same eccentricity as for texture #8 but it tends to drift toward the center slightly during the analysis period. Thus, a second difference is found between solutions for subject 2 and subject 3; the appearance response for subject 2 does display variations linked to the different stimulus patterns.

The variations among solutions for different texture stimuli are maintained in the pattern reversal analysis, also amendable only to the

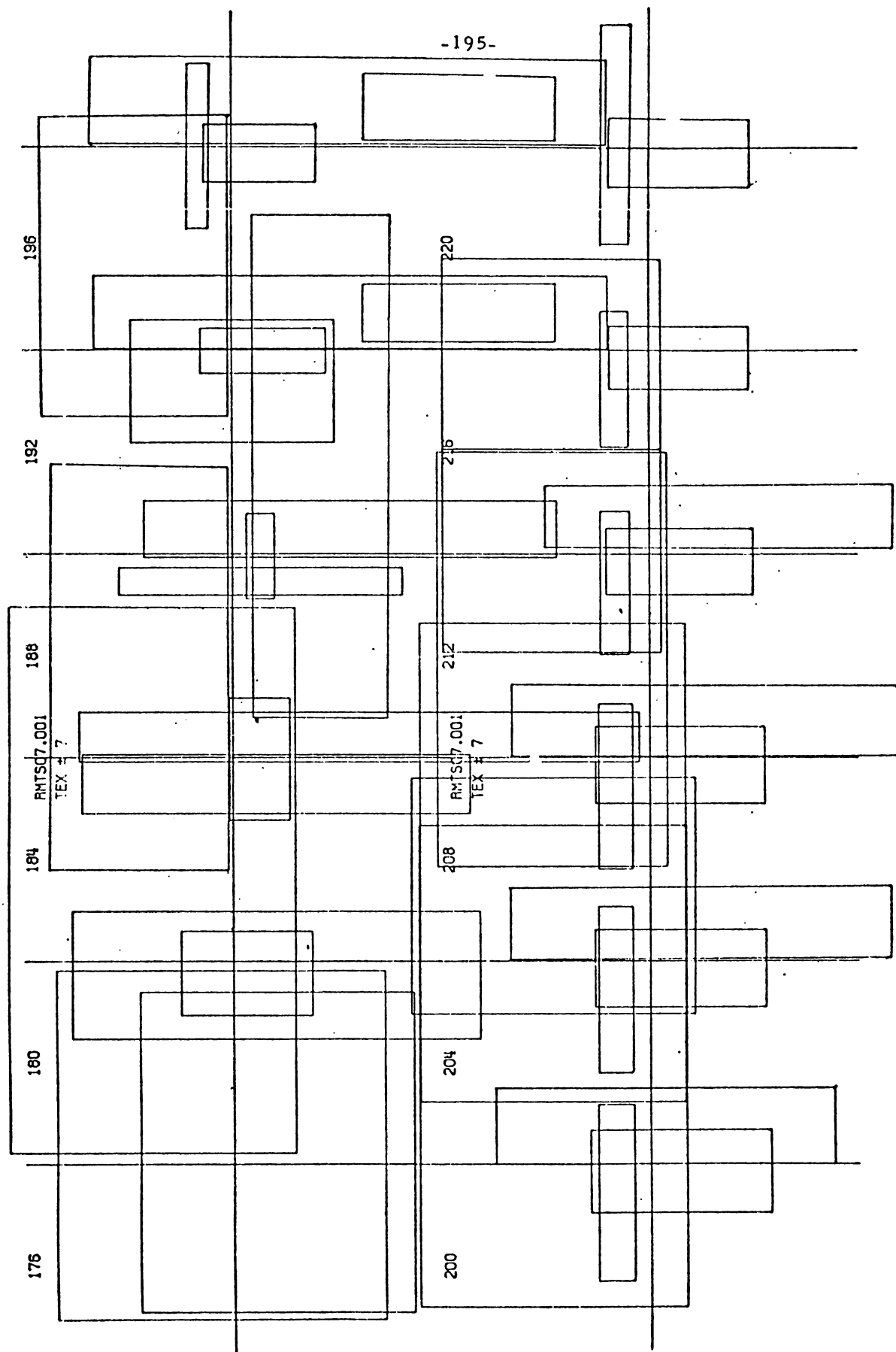


Fig. 5.39 Sub. 2 Tex. 7 2 sources 176-220 ms after appearance

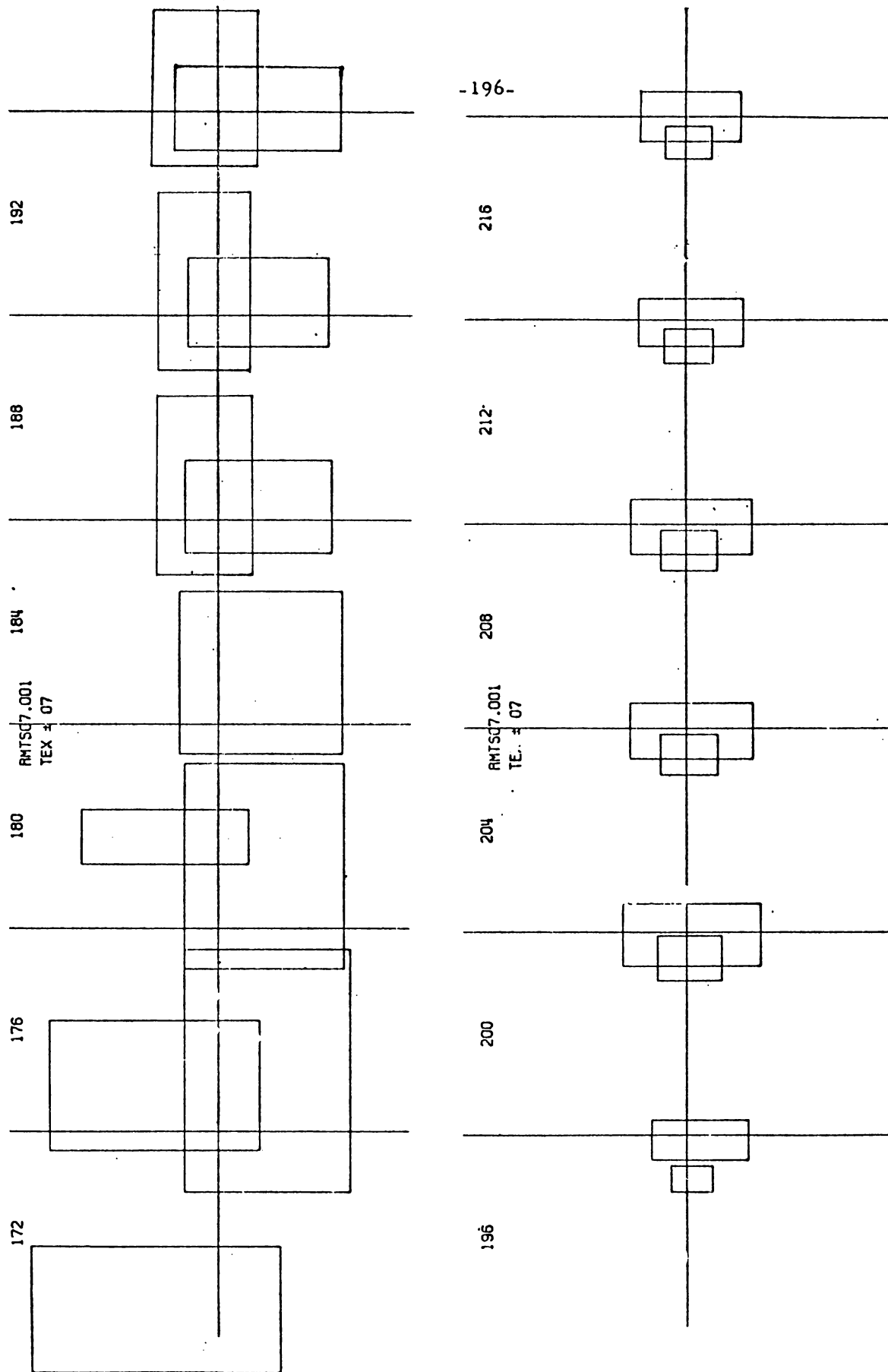


Fig. 5.40 Sub. 2 Tex. 7 single source 172-216 ms after appearance

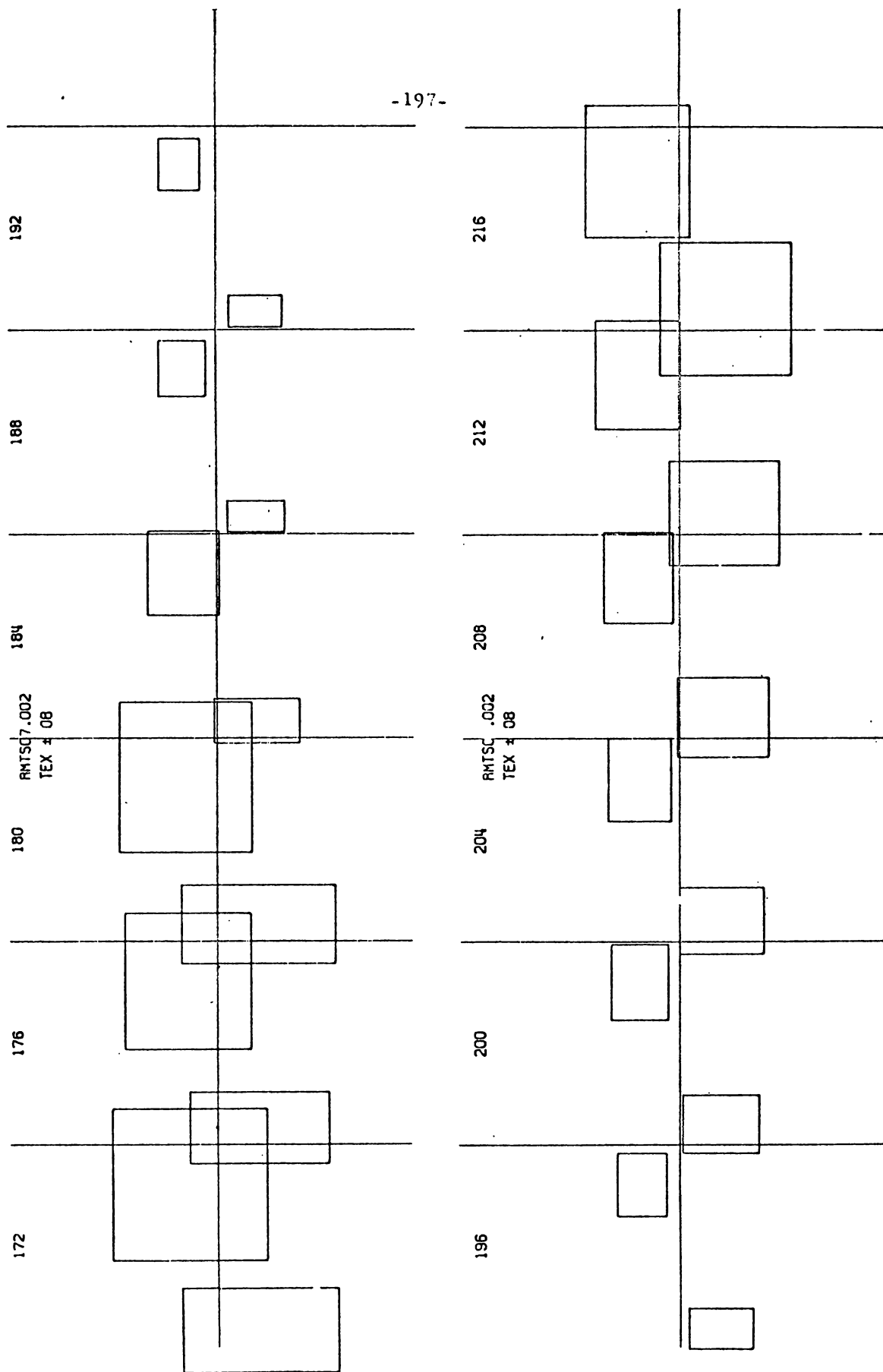
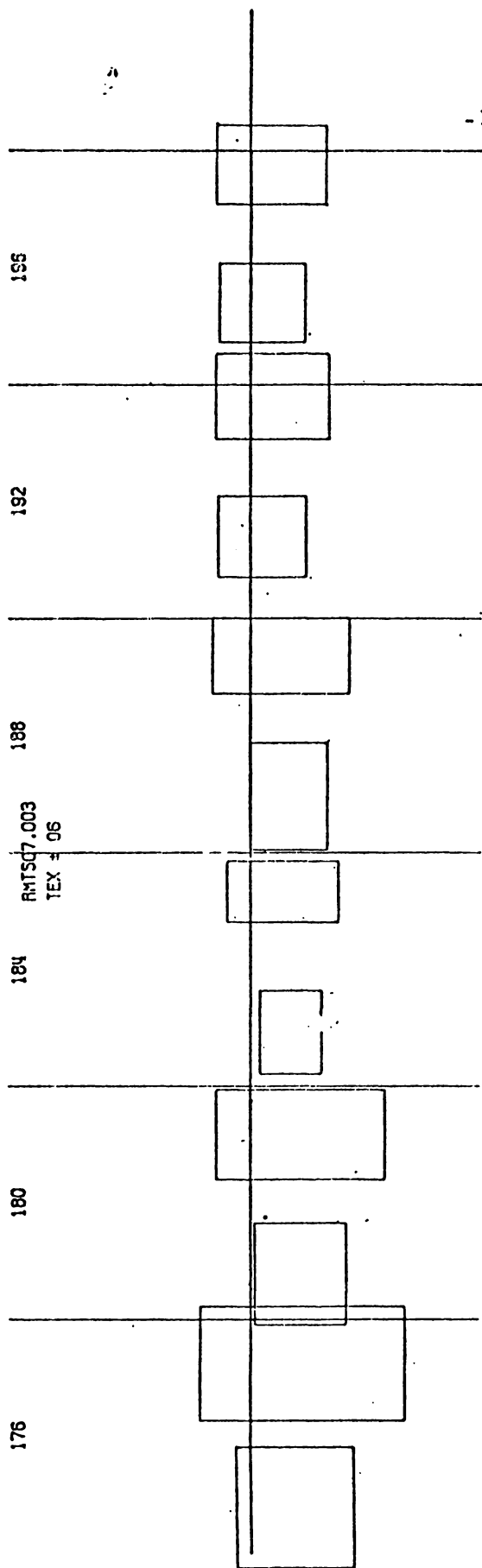


Fig. 5.41 Sub. 2 Tex. 8 single source 172-216 ms after appearance



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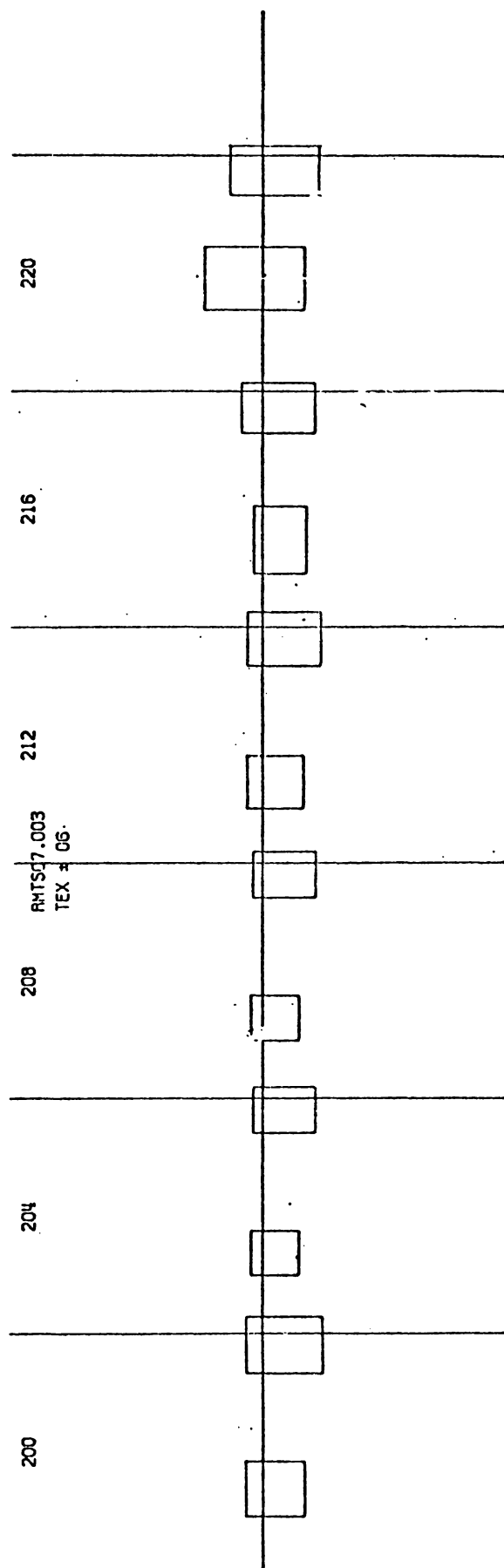


Fig. 5.42 Sub. 2 Tex. 6 single source 176-220 ms after appearance

single-source model. In the reversal analysis, no large eccentricity variations are found in the solutions for the different stimuli (Fig. 5.43-5.45). The solutions do show variations in source behavior during the time course of the reversal response. The texture #7 source is again odd man out moving away from the center of the model while the texture #8 and texture #6 solutions move inward. Hence, the solutions for subject 2, while not perhaps as intriguing as the subject 3 results, nevertheless, retain the capacity to distinguish among responses to the various texture stimuli.

The analysis for subject 1 data retains the common texture response discriminability of all the solutions while presenting us with yet another variation of that theme. For this data set, a two-source solution produced quite acceptable results. As shown in Fig. 5.46-5.48 and 5.49-5.51, both appearance and reversal solutions follow quite similar motion patterns and occupy similar regions within the model. The only exception to the foregoing is the behavior of the appearance solution for texture #4. In general, the two-sources are initially found at 144-148 ms following either stimulus event oriented on opposite sides of the midline, the rightmost one quite high on the Z axis of the model and close to the midline, the leftmost one much lower on the Z axis much farther away from the midline. The usual behavior of the sources is for the uppermost one to retain its position while the other moves laterally to a point almost directly beneath it. The motion of the sources takes place over the time period of 144-192 ms following the stimulus event. In the one exceptional case of texture #4, the sources are found quite close together in the right hemisphere at 148 ms but

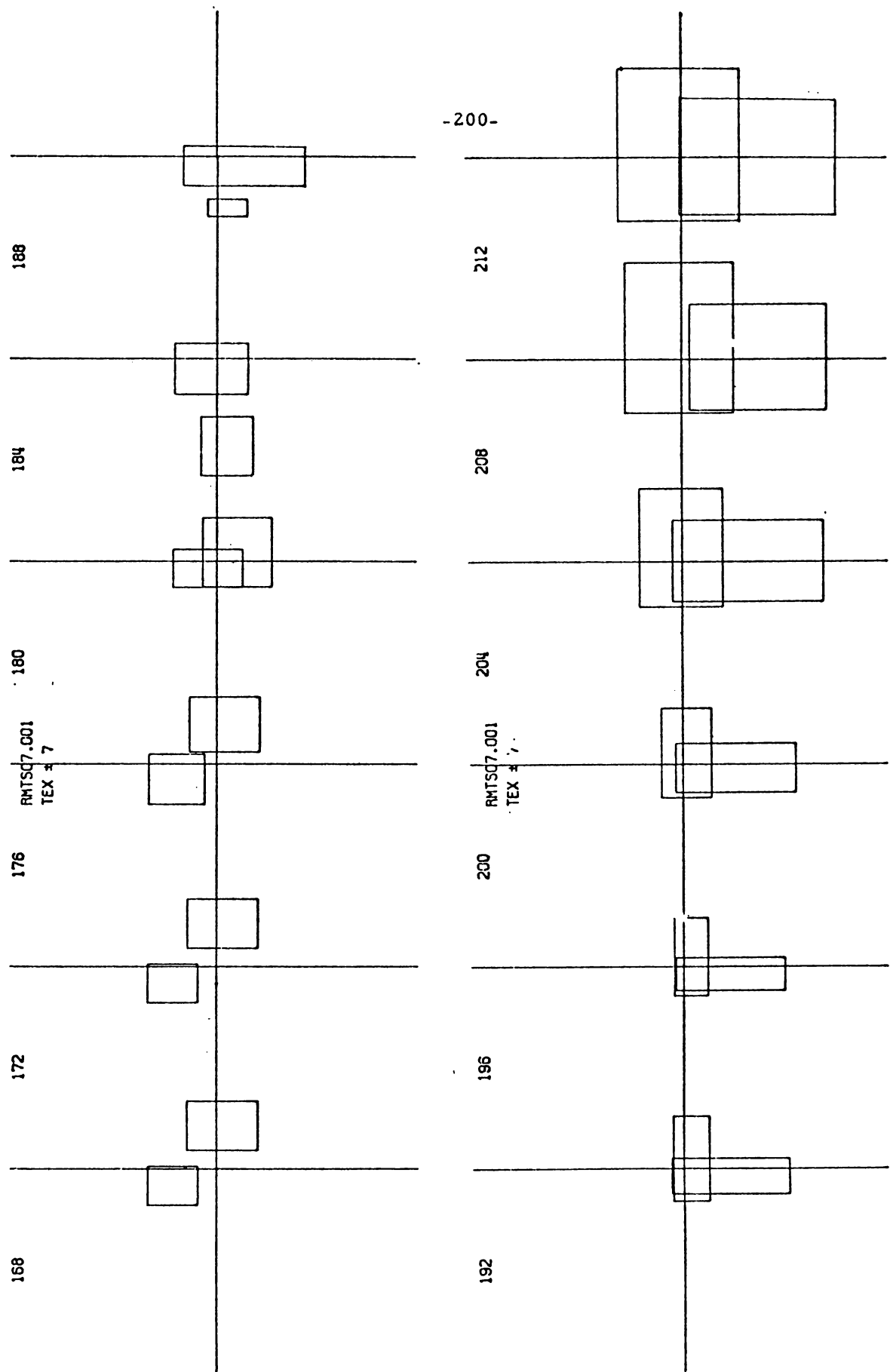


Fig. 5.43 Sub. 2 Tex. 7 single source 168-212 ms after reversal

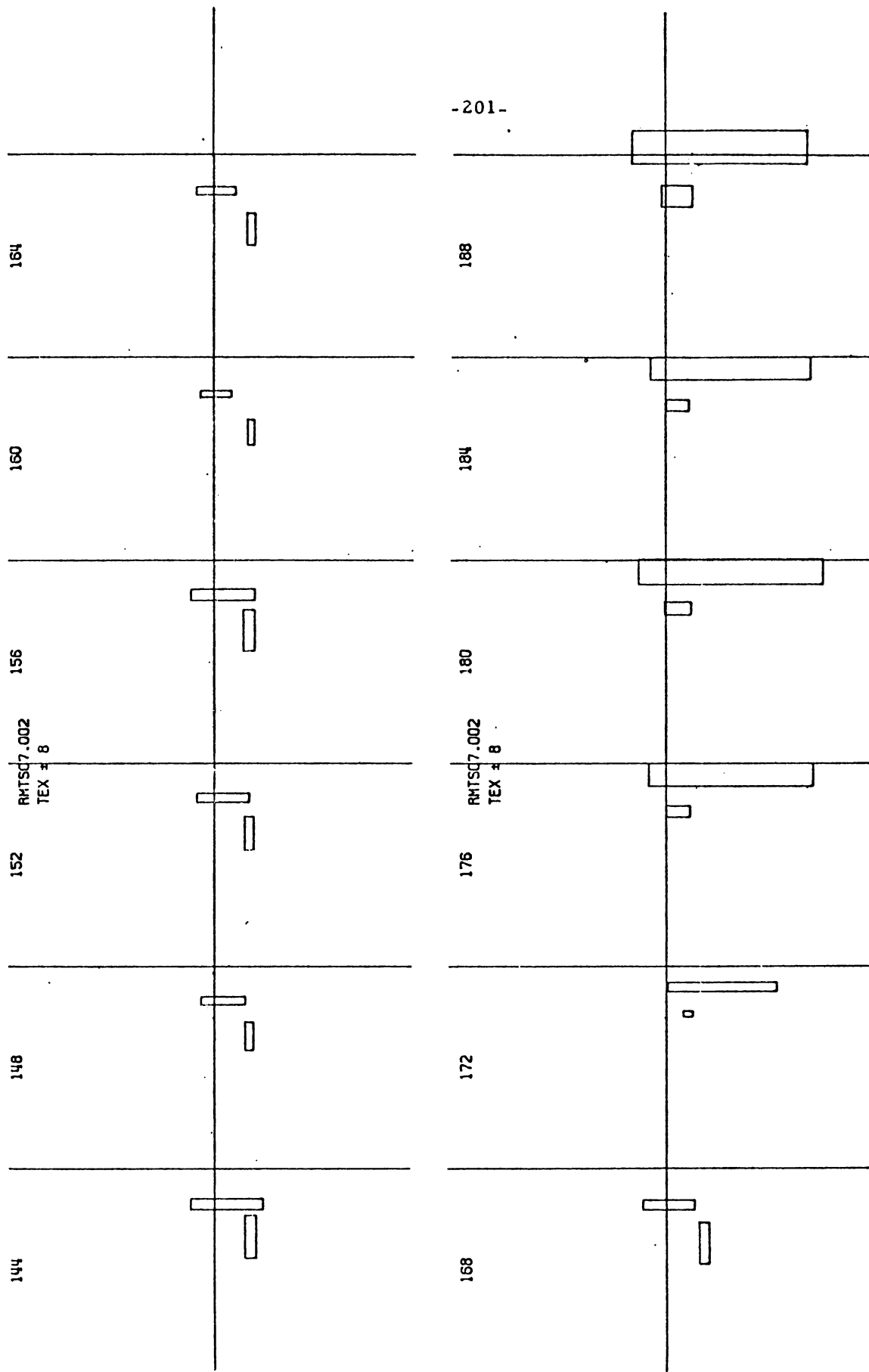


Fig. 5.44 Sub. 2 Tex. 8 single source 144-188 ms after reversal

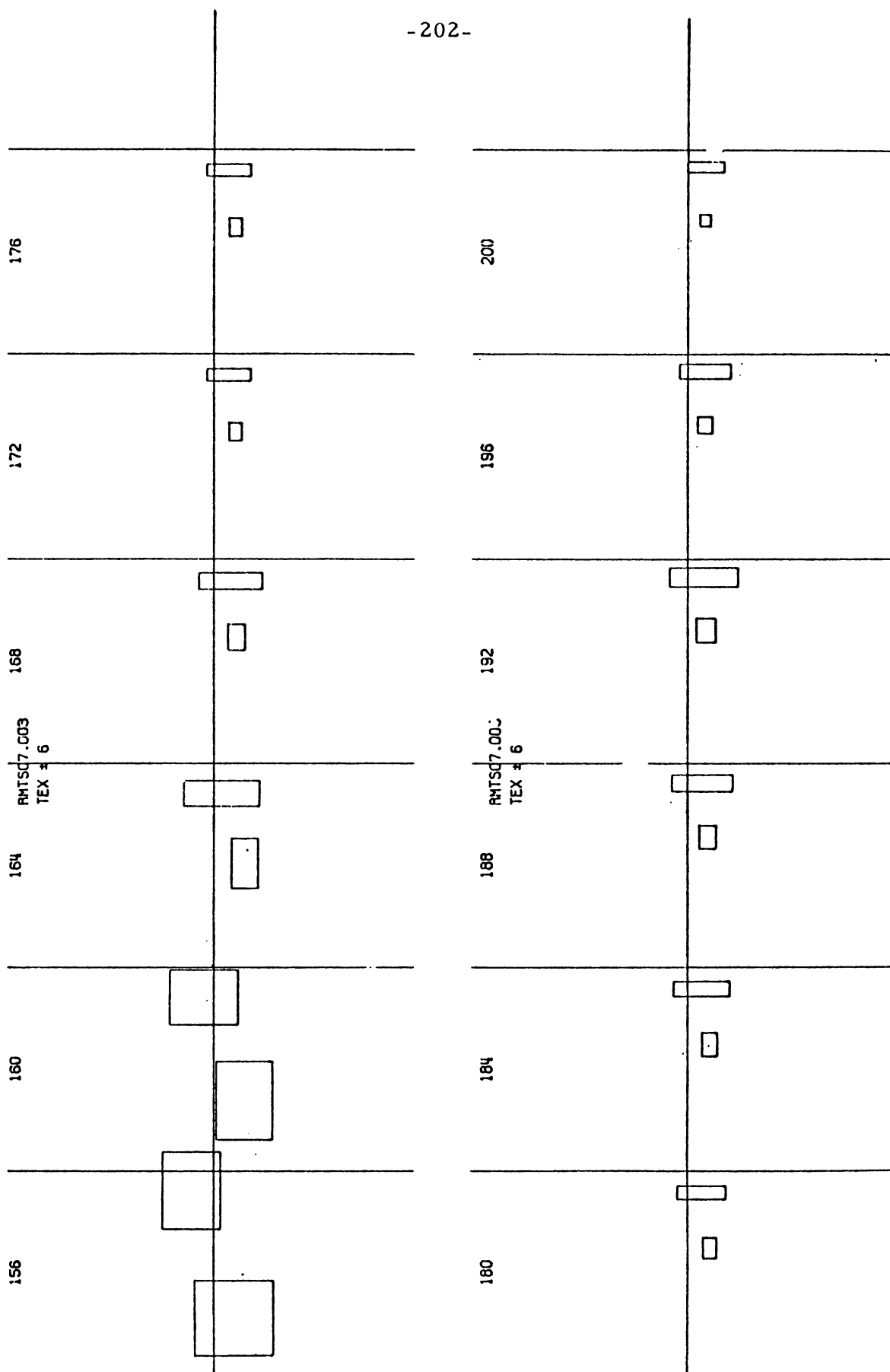


Fig. 5.45 Sub. 2 Tex. 6 single source 156-200 ms after reversal

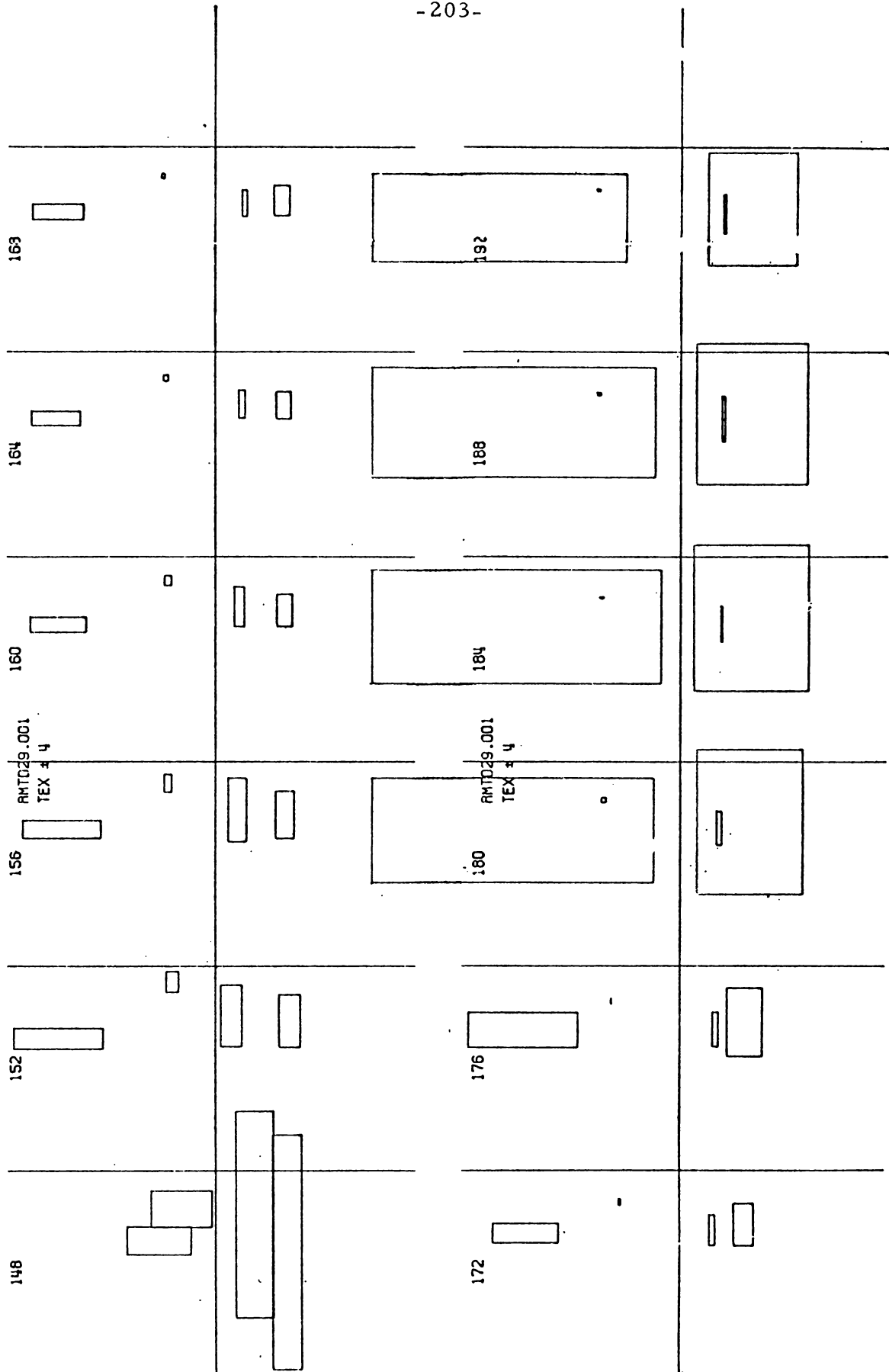


Fig. 5.46 Sub. 1 Tex. 4 2 sources 148-192 ms after appearance

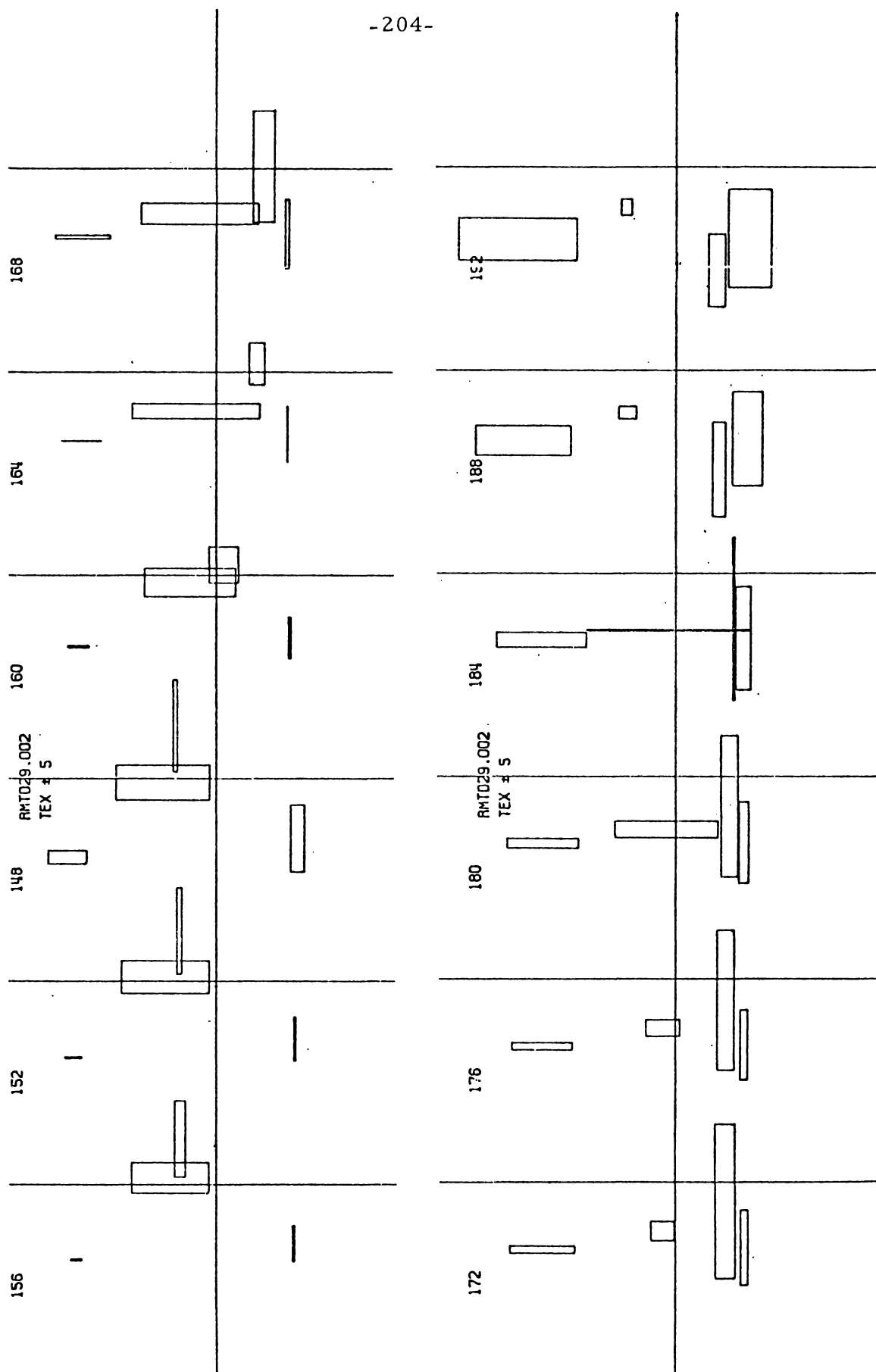


Fig. 5.47 Sub. 1 Tex. 5 2 sources 148-192 ms after appearance



Fig. 5.48 Sub. 1 Tex. 13 2 sources 148-192 ms after appearance

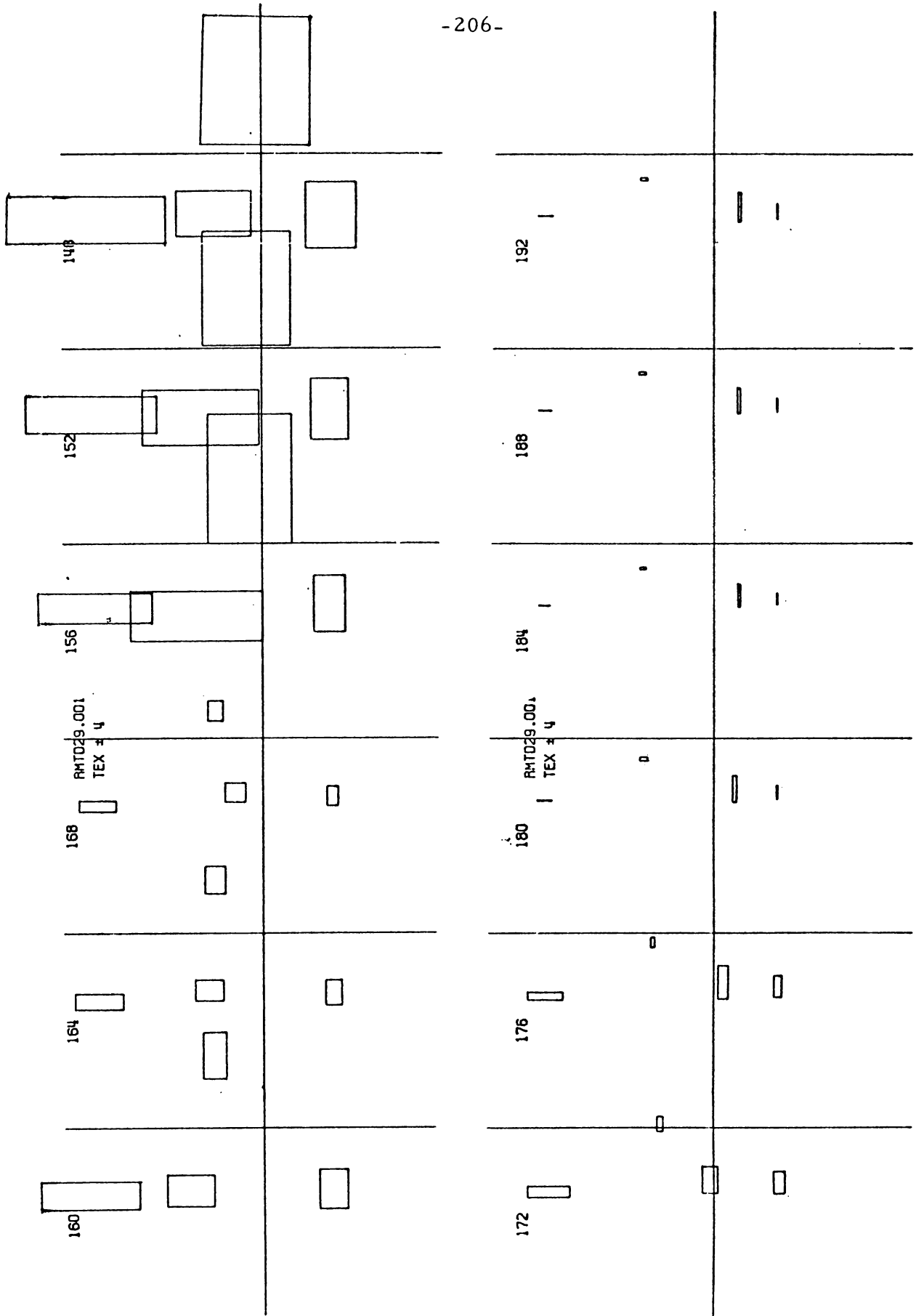


Fig. 5.49 Sub. 1 Tex. 4 2 sources 148-192 ms after reversal

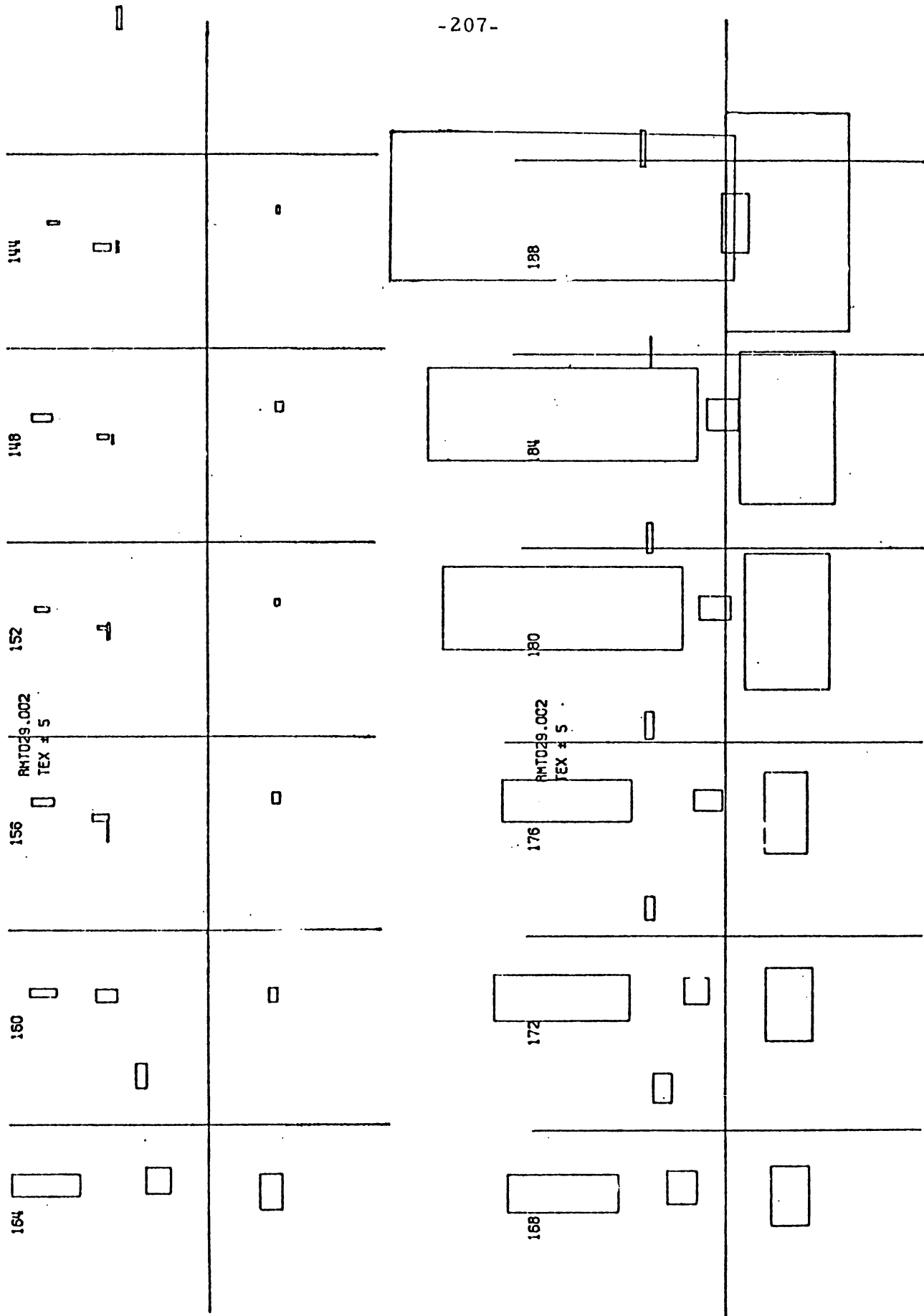


Fig. 5.50 Sub. 1 Tex. 5 2 sources 144-188 ms after reversal

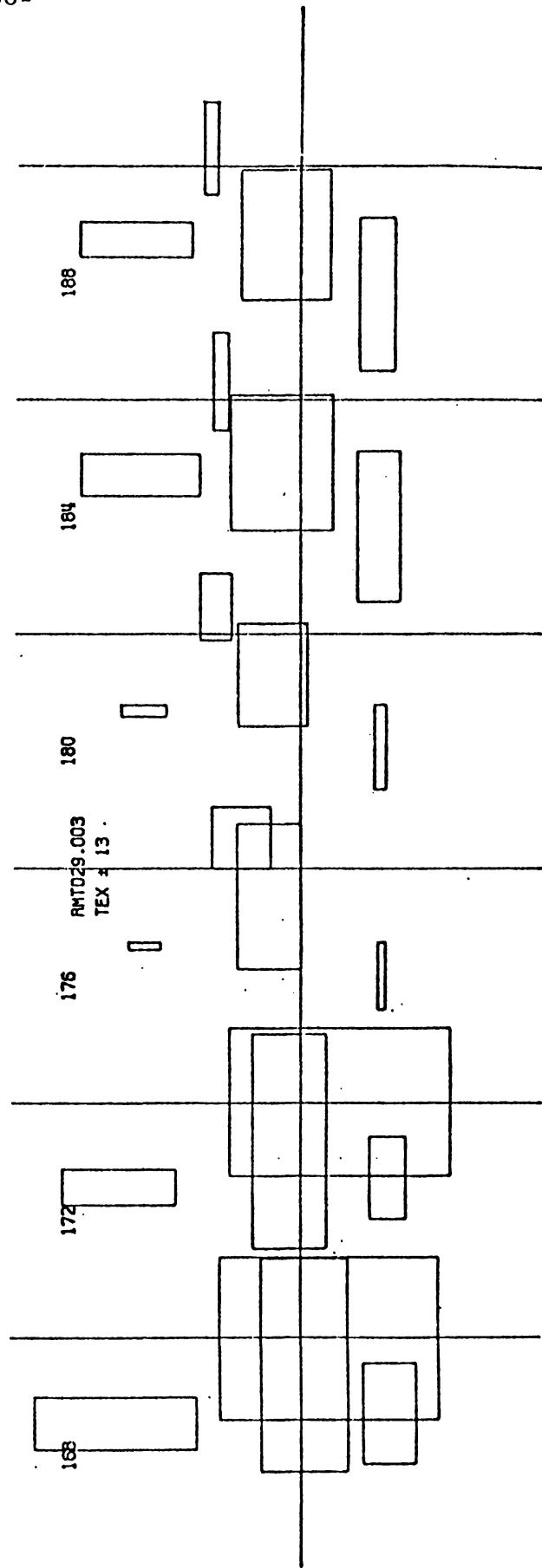
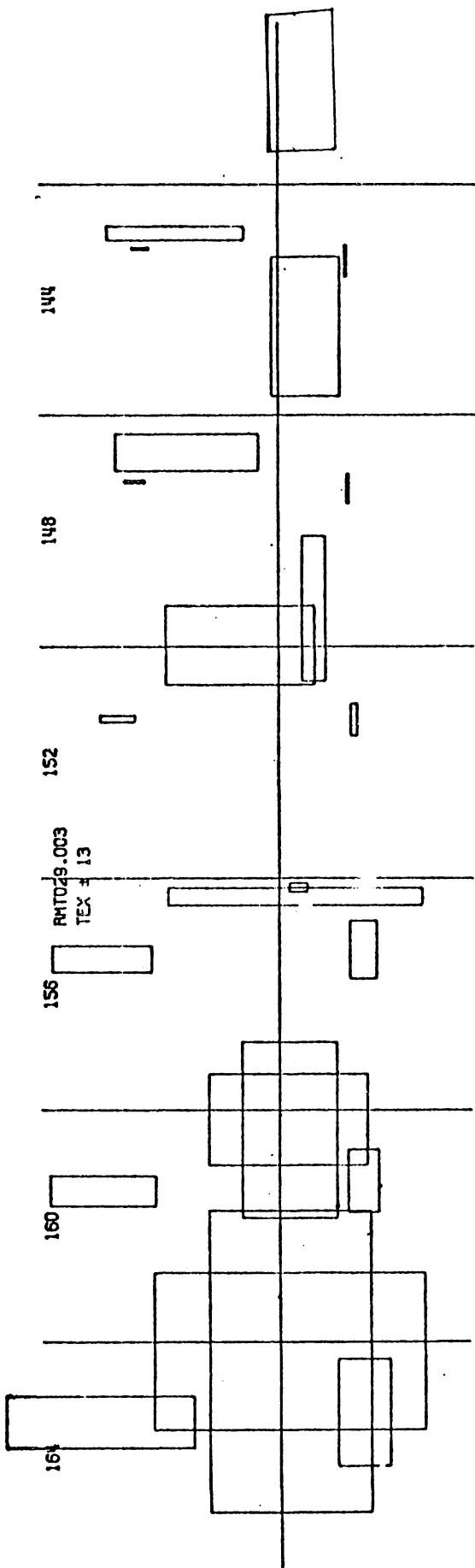


Fig. 5.51 Sub. 1 Tex. 13 2 sources 144-188 ms after reversal

then shift to the aforementioned starting position at 152 ms and conform to the general behavior pattern thereafter.

The differences displayed by the solutions for subject 1 are, with the one exception mentioned, entirely a matter of the amount of source eccentricity displayed at the start of the motion behavior. The appearance solutions display a uniform increase in the leftward displacement of the lower source in the order texture #4, texture #5, and texture #13. The sources for texture #13 are remarkably far apart compared to those for textures #4 and #5. The latter two textures still show a significant difference in separation at the early latencies of the analysis. The variation of source separation is somewhat obscured for the reversal response, as the position of the leftmost source in the texture #13 solution has quite wide confidence boundaries. The difference in separation of sources for texture #4 and texture #5 is also not quite as great for the reversal analysis as it is for the appearance.

Hence, based on the results of analysis for 3 different subjects, we may state with certainty that the source analysis does reveal in a very lucid manner subtle differences in scalp potential fields evoked by pattern stimuli. This is a result of major importance to the present study. There was no certainty at the beginning of this work that any variations in pattern vision could be detected by our techniques. We now have obtained the electrophysiological measure of pattern response variations needed for the evaluation of our hypotheses concerning the perception of the test stimuli. In the next and final chapter we can now draw together and compare the two separate studies of this investigation.

VI. SUMMARY AND CONCLUSIONS

The work of this investigation began from a single idea which quickly evolved into two separate lines of inquiry so that finally the task of reconciling them is no simple job. This chapter, therefore, is presented not as a neat and well substantiated conclusion, but rather as a hypothesis which suggests itself teasingly from within the nooks and crannies of the great mass of data collected in the previous chapters. Any number of experiments can be devised to explore and possibly refute the following speculations. Our final hypothesis is thus offered up as a lamb to wolves with the hope that perhaps in tearing it up, the wolves may come upon something of substance. Let us begin by summarizing the hard facts obtained from our two experiments and then consider what possible theories we might build upon them.

Basic Experimental Results

The results of the confusion experiment give a quantitative measure of the relative ease with which each member of our test pattern group can be spontaneously distinguished from each of the other members. The results show that certain pairs of textures are easy to distinguish while other pairs are easy to confuse. By applying equal quantities of powerful numerical analysis and straight-forward visual inspection, various conclusions were drawn in Chapter V about the properties of the different textures which contributed to their relative confusability.

The evoked potential tests measure the median electrical activity on the scalp of subjects viewing repetitious appearances and reversals of certain textures. The total illumination presented to the subject

is the same for every test pattern and remains constant throughout all stimulation events. The appearance and reversal events cause the illumination at all points throughout the pattern to switch by large increments. The local brightness changes throughout the retinal image are the stimulus for the fluctuation in median scalp potential differences which occur after those events. The VESP tests show that for a given subject, the expected value of median activity on the scalp is nearly constant for all the different patterns used in stimulation. A very sensitive numerical analysis, taking into account the activity at many sites over the scalp, is able to detect subtle differences in the VESP's for different textures, however. The differences in VESP's are necessarily due to the differences in the patterns of illumination on the retina and thereby linked to the differences in the probabilistic rules that generated those patterns.

Comparison of Electrophysiological and Psychophysical Results

The basic result of the confusion experiment is the matrix of relative object dissimilarities. The dissimilarities for the patterns used in VESP experiments for each subject are listed in Table 6.1. Beside the numerical dissimilarities in Table 6.1 for each subject, a structure is shown representing the relative positions of the test patterns in some hypothetical three-dimensional space. The patterns chosen for VESP tests encompassed both pairs which were very easily distinguished in the confusion experiment and a few pairs which were relatively easy to confuse. The primary concern of the VESP tests being to sense variations in the scalp potentials for different patterns, the selection of patterns was biased toward those with large differences.

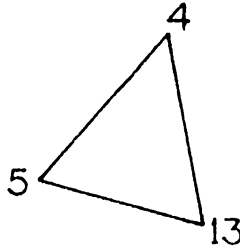
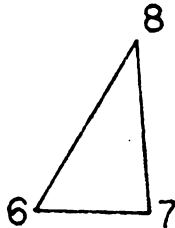
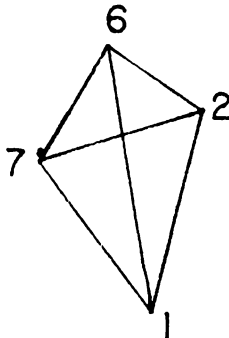
Subj. 1				
Tex. Pair	Dissimilarity	Metric Structures	Tex.	description
4-5	1		4	nVnH
4-13	1		5	pVnH
5-13	.9		13	pD
Subj. 2				
Tex. Pair	Dissimilarity			
7-8	.9		7	pH
7-6	.6		8	nH
8-6	1		6	nVpH
Subj. 3				
Tex. Pair	Dissimilarity			
7-1	1		1	pV
7-6	.7		2	nV
7-2	.9		7	pH
1-6	1		6	nVpH
1-2	1			
6-2	.6			

Table 6.1 Dissimilarities for VESP Pattern Stimuli

Let us contrast the behavior of the source solutions during the time intervals analysed in Chapter V for the VESP's of each subject, shown schematically in Figure 6.1, with the relative dissimilarities among the texture stimuli. In the case of subject 1, the three patterns shown were all easily distinguishable. Textures #5 and #13 were 5% more likely to be mistaken for each other than were #5 and #4 or #13 and #4. However, subject 1 correctly distinguished textures #5 and #13 on 95% of all trials. The differences among the source solutions for textures #4, #5, and #13 are most apparent in the sequence following pattern appearance. The initial behavior of the texture #4 solution is quite different from the others. The #5 and #13 solutions are different in the amount of source separation and thus the absolute locations they occupy during the response but are similar in their overall behavior. Thus, the VESP results exaggerate the perceptual differences of texture #4 from the other two textures. The good deal of similarity in the solutions for #5 and #13 exaggerates the 10% perceptual confusion rate between these textures. Thus, the perceptual and electrophysiological results for subject 1 are quite compatible.

In the case of subject 2, two of the three textures used in VESP tests were significantly easier to confuse with each other than with the third. The dissimilarity value .6 between textures #6 and #7 means that subject 2 confused these patterns 4 times out of the 20 trials. He only made 1 error out of 20 chances for the #8-#7 pair and no errors for #8-#6. The (single source) solutions for VESP's from textures #6, #8, #7 have aspects which are compatible with the dissimilarities among these textures. However, some of the differences between

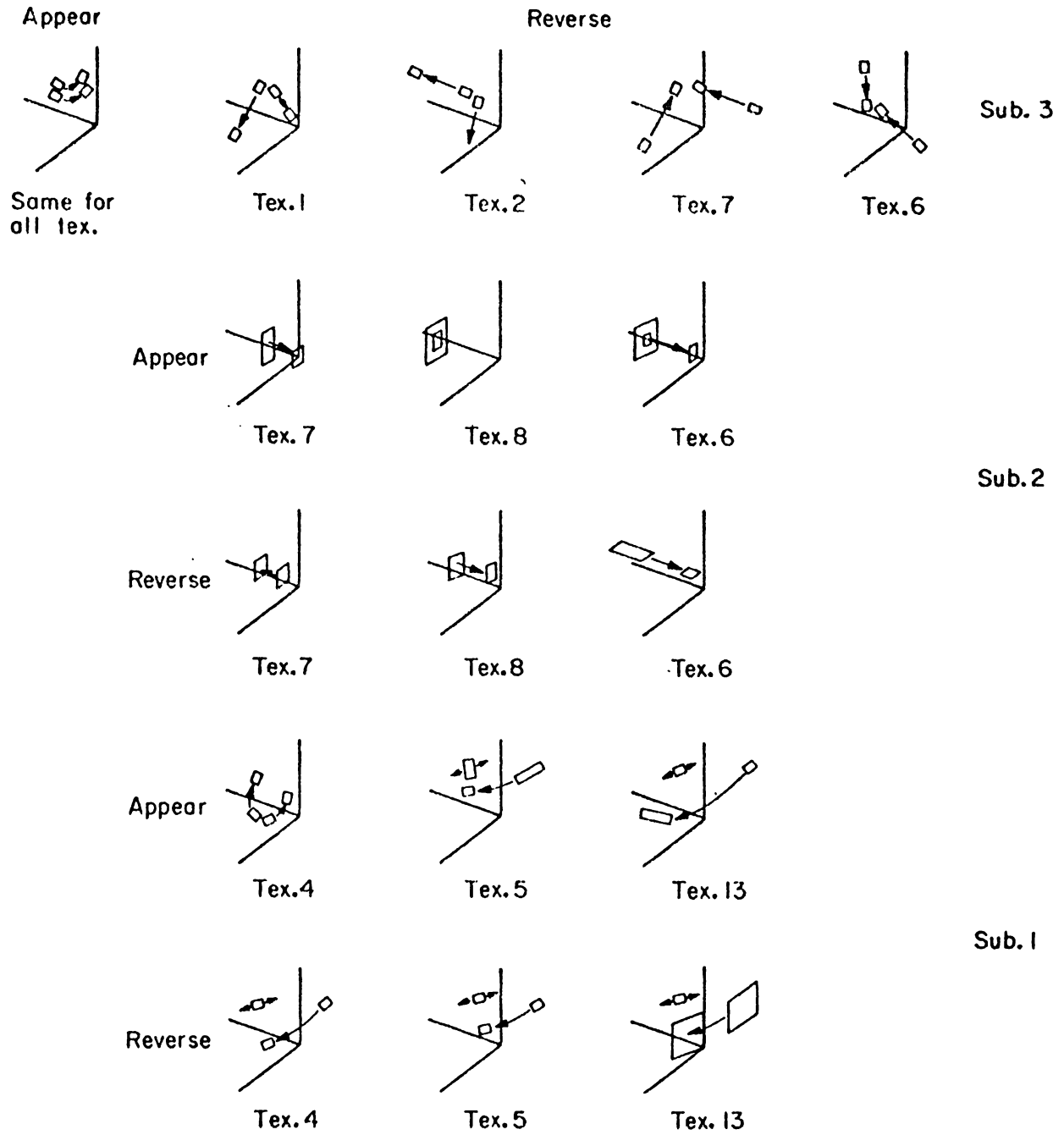


Fig. 6.1 Schematic loci of source behavior for each subject.

source solutions are contrary to the perceptual dissimilarities. In the solutions for the appearance response, the source for #7 gravitates down the positive y axis all the way to the origin or center of the model head. The sources for #6 and #8 never are found at the origin and occupy a region of the outer y axis never visited by the #7 solution. The #6 solution does move toward the origin during the response while the #8 solution undergoes little net displacement at all. In the reversal response sequence, the difference between #7 solution and the other two is obvious. The #7 solution starts close to the origin of the model head and moves outward while the #6 and #8 solutions do just the opposite motion. Hence, in total, texture #7 seems to be the odd-man-out for the VESP results, while the perceptual experiment shows #8 to be the most different of the three stimuli shown to subject 2. However, arguments can be made, particularly for the appearance sequence, in favor of texture #8 having the most different source solution.

The solutions for subject 3 VESP model sources and the perceptual dissimilarities among the texture stimuli share various points of compatibility. However, ambiguities are also apparent in the contrasting of VESP and perceptual results for subject 3. There is some question of scaling the differences among the solutions for each texture. It seems logical to group the solutions which begin with two sources far apart that converge toward each other separately from those solutions having two sources in proximity that then diverge. By performing this grouping, we see that solutions for textures #7 and #6 are together just as the perceptual dissimilarity between these textures is relatively low. However, solutions for #1 and #2 are grouped together

since their sources begin in proximity and diverge, yet subject 3 never made an error in distinguishing these two textures. The convergence/divergence criteria divides the solutions for textures #7 and #1 which have perceptual dissimilarity of 1.0 but also divides textures #6 and #2 which have dissimilarity of 0.6.

Hence, we see that a direct comparison of psychophysical and electrophysiological results yields mixed results about the relationships of these quite different responses to our test patterns. The basic problem we have is in ranking the differences among the solutions for the VESP's. While our dissimilarity measures tell us directly how different the perception of one pair of textures is from the perception of another pair, there is no simple criteria for ranking the source solutions to our VESP data. Thus, in order to further interpret the VESP data we must begin to incorporate the various theories we have developed concerning the perception of the test stimuli from our dimensionality and scaling analysis.

Interpretation of Source Solutions by Means of Perceptual Hypothesis

Let us reconsider our hypothesis concerning the perceptual components of the textures used in VESP experiments. For the three stimuli for subject 1, our theory goes as follows. Pattern #4 (nVnH) should elicit a pure granularity percept only. Pattern #5 (pVnH) elicits two perceptual components: average graininess and a very strong verticality percept. Texture #13 also has two components: clumpiness and diagonality. Thus, textures #5 and #13 have somewhat similar granularity components and differ primarily according to independent directionalities; vertical and diagonal. Texture #4 has only the strong

smoothness component and hence could be expected to receive different, perhaps simpler, processing than the two-dimensional textures #5 and #13. In as much as the model source solutions bear out our hypothesis that VESP's for texture #4 should be different from those for #5 and #13 (which should be similar), we need go no further with our consideration of data for subject 1.

Our initial interpretive problems arose with subject 2. The source solutions seemed to indicate texture #7 could be the odd member of the #7, #8, #6 group. The dissimilarity values for the three textures favored perceptual nearness for #6 and #7 with #8 being quite different from the latter two. Our theory of the perceptual components for these textures, based as it is upon the dissimilarities measured for all subjects and all textures, likewise predicts that texture #8 should be the most different of the test stimuli. All stimuli are two dimensional textures eliciting strong granularity and directionality percepts. It is in the directionality percept that texture #8 (nH) differs by a 90° rotation from both #7 (pH) and #6 (nVpH). Texture #8 should produce a strong verticality percept while both #7 and #6 should elicit horizontality percepts that differ only slightly in strength. As far as their granularity aspects are concerned, the three textures span a range from clumpy (#7) to smooth (#8) with #6 at a neutral position equidistant between the two. Thus, the VESP models are immediately compatible with the granularity variations in the stimuli in as much as the #7 and #8 solutions in both appearance and reversal responses are the most different with the #6 solution lying midway between them in terms of the overall behavior of the solutions. What we do not see in the source

solutions is the segregation of the response to pattern #8 as occurs in our perceptual models. However, let us recall that pattern #8 shares the same directionality percept as #7 and #6, it differs from them merely by a change of sign along that principal component axis in our perceptual 3-space. Hence, a possible explanation of the failure of the source solutions to discriminate between the verticality of #8 and the horizontality of #6 and #7 could be that the mechanism which processes the sign or orthogonality information concerning the common directionality percept of the three textures is too subtle to be detectable by the present analysis. Alternatively, orthogonality information may not exist at the stage of processing we are able to interrogate via scalp potentials. The fact that texture #8 is at 90° to #7 and #6 may have already been digested previously at some earlier latency or non VESP significant location.

Thus, we may conclude that our VESP model variations for subject 2 are primarily linked to the granularity differences among the stimuli. Perhaps a much closer inspection of the source solutions than the one presented here might show systematic differences that encompass the orthogonality relationship among the patterns. However, if orthogonality mechanisms are present in the VESP's for this subject, they are certainly secondary to the granularity mechanisms and certainly not as distinct as those revealed in the psychophysical analysis. Let us recall that the VESP's for this subject could only be fit by a single source model in contrast to the 2-source solutions for the other subjects. For whatever reason, the VESP's for subject 2 do not have the resolution for a 2-source fit and hence, perhaps orthogonality infor-

mation concerning the stimuli may thereby be lost.

Let us now reconsider subject 3. For this subject, four 2-dimensional textures were used whose perceptual configuration is shown in Table 6.1. Our original grouping of the VESP solutions along the lines of diverging and converging sources was so incompatible with the perceptual dissimilarities among the stimuli that there is little chance of reconciling it with the theories derived from those perceptual measures. Hence, armed with our new theories, we must take a fresh approach in grouping the VESP solutions.

Subject 3 was found to differ from the others in that his major perceptual discriminant was the directionality and not the granularity qualities of the stimuli. Hence, a good hypothesis would be to divide the VESP solutions according to the directionality differences in the stimuli. The four stimuli consist of one with a strong verticality component, two with equal amounts of strong horizontality, and one with very strong horizontality. Let us then characterize the VESP for texture #1 (pV) as a strong verticality response and lump the three solutions for textures #2 (nV), #7 (pH), and #6 (nVpH) in a group characterized by the horizontality percept.

The two sources for texture #1 follow slightly divergent downward loci during the critical response period following pattern reversal. Within the period analyzed of 40-90 ms duration, the #1 source solutions make no upward motion whatsoever in our model head. A quick inspection of the solutions for the horizontality stimuli shows that in each at least one of the two model sources transverses an upward path. Hence, we may associate the purely downward locus taken by the #1 solution

with the perception of verticality for subject 3.

Now the unifying aspect of the #2, #7 and #6 solutions is the presence of an upward motion for at least one source. Thus, the presence of some upward motion seems to indicate the perception of horizontality by subject 3. The textures with theoretically approximate amounts of horizontality differ along an increasing scale of clumpiness in the following order. Texture #2 (nV) is quite smooth and should elicit as strong a horizontality percept as texture #7 (pH). Texture #6 (nVpH) should elicit a somewhat stronger horizontality percept than that of #2 or #7 while lying midway between them in terms of its granularity quality. Finally, texture #7 (pH) is the clumpiest of the three horizontal textures. Texture #7 in fact should be identical to texture #1 (pV) in terms of granularity and differ from #1 only by virtue of a 90° rotation.

Thus, we see in subject 3 quite opposite VESP solutions for two textures of identical granularity but orthogonal directionality. The sources for the clumpy vertical texture #1, start quite close together in the upper right model hemisphere and diverge downward. The sources for the clumpy horizontal texture, #7, start quite well separated and low in the model and converge upward. The behavior of the solutions for the textures differing only due to directional orthogonality is quite likely the most opposite pair of behavior patterns of all the solutions for subject 3. This result fits nicely with the perceptual characterization of subject 3 as the odd man out of the 3 subjects who used directionality and not granularity as the prime discriminant for distinguishing among members of the texture group.

The differences among the solutions for the three horizontal tex-

tures are, as aforementioned, ascribable to the granularity variation among them. The behavior of the sources for texture #2 is quite opposite to the behavior of the #7 solution while the #6 solution fits neatly between #2 and #7 as it contains aspects of both. Texture #6 (nVpH) is a combination of the singular connectivities represented in texture #2 (nV) and #7 (pH). By intentionally looking for it, we can tease out evidence that the source solution for texture #6 VESP might be some combination of the solutions for #2 and #7. The solution for #7 has two sources converging toward a midway region in the right hemisphere of our model head while the solution for #2 has two sources diverging from approximately the same region. The #6 solution has two converging sources, one of them quite similar to one of the #7 sources and the other leaving an upper region of right hemisphere that one of the #2 solution sources frequents. Indeed, only the #6 and the #2 solutions have sources occupying the extremely high region of the right hemisphere. We might venture that this region of our model is associated with the perception of smoothness as created in our texture patterns by the use of nearest neighbor negative connectivity.

Since each solution for our four stimuli occupies somewhat different regions within our model, we might extend our above proposition to include the association of certain regions with pure clumpiness and others with the combination of clumpiness and smoothness, etc. Hence, we begin to make a distinction between the motion of our source solutions and the general areas the sources frequent. The source motion we have associated with the perception of directionality and now we associate the source locations with the perception of granularity. These

conclusions seem to fit quite well to our analysis of results for subject 3 from both VESP and psychophysical tests.

With our other two subjects, whose primary pattern discriminant was granularity, we find ambiguities in making as neat associations as we could for subject 3. We can associate location of solution sources with the granularity aspects of the stimuli for each subject. The motion behavior of the sources is only clearly associated with directionality perception in the case of subject 3. For subjects 1 and 2, source motion may carry both directionality and granularity connotations. For subject 2 our uncertainties are of course, due in part to our inability to find a 2 source fit for his VESP data. In the case of subject 1, we do find something akin to the source motion reversal of subject 3 which we again associate with directionality perception. Unfortunately the stimuli used for subject 1 (just as for subject 2) did not encompass both orthogonality and granularity qualities as well as those used on subject 3. The direction for further testing is thus indicated to explore the present interpretations.

General Conclusions

The interpretation of our VESP analysis by the use of hypotheses generated from our psychophysical study leads us to the following conclusions. The most optimistic implication we can formulate is that our VESP analysis can predict not only characteristics of the actual stimulus being shown the subject but in fact how the subject perceives that stimulus. Thus, we can link VESP signals with perceptual processing of sensory stimuli and the outcome of that processing. Once a subject's response parameters have been characterized for a particular class of visual

patterns, his response to an unknown member of that class tells us not which member he saw but which member he thinks he saw and moreover, how certain he is of that perception.

On a somewhat less optimistic vein, we may conclude that our VESP technique reveals the existence of information in the scalp potentials concerning the perception and discrimination of the various members of our texture group. In this way, we may claim that our VESP analysis substantiates our earlier conclusions from psychophysical testing. The differences revealed among the responses to different textures by our source analysis are compatible with our theories of the perceptual components stimulated by those textures.

Finally, we may even attempt an anatomical interpretation of our VESP conclusions. It seems plausible to ascribe differences in the motion behavior of our source solutions (i. e. convergence, divergence) which occur in the same region of our model head to differences in activity of a common neural population. Natural also would be the suggestion that source solutions in distinctly different locales of our model probably arise from the activity of distinctly different populations of neurons. Hence, we might hypothesize that textures with distinct differences in granularity are processed by different neuronal populations while differences in directionality among textures of the same granularity (at least in so far as a 90° rotation is concerned) are handled by different kinds of processing within a common population.

Our last conclusion concerning directionality is incomplete because of the small amount of VESP test data for diagonal textures. Our perceptual theories allocate an independent perceptual process for diagonal

stimuli. We also concluded that any orthogonal stimuli (vertical-horizontal or the two possible diagonals) would be handled by a single perceptual component via some mechanism which we represented as a sign-change along the direction of that component in our perceptual 3-space. The only comparison of a diagonal texture with a horizontal or vertical texture (in the data of subject 1) shows the source solutions are found in quite different locations. This result is clouded by the fact that the textures of interest had distinct granularity as well as directionality differences. There remains the suggestion however, that obliquely oriented textures may be handled by different cell populations than vertical or horizontal textures.

Implications of These Conclusions

While it is difficult to substantiate the suggestions of an anatomical basis for our source solutions from the results of this study, there are a host of implications for further studies in both VESP's and single cell recordings which could prove or disprove our contentions. Our findings are not incompatible with the work of the various neurophysiologists discussed in Chapter II; Hubel and Wiesel, Pollen, etc. Their finding that receptive field sizes tend to be quite similar within a fixed region of visual cortex, for example, could support our conjecture that textures with appreciably different granularity could be processed by separate neural populations. The finding that cells which show strong excitation for certain orientations of bar gratings but are immediately silenced for bars of the orthogonal orientation also might fit with our suspicions that orthogonally oriented textures are handled by drastically different processes within a common cell population.

An interesting line of further VESP experimentation is suggested from the foregoing. Apply the VESP analysis to data from grating stimuli of the same orientations as our textures. Provided good localizations can be obtained for the gratings, a comparison of their sources in terms of both location and motion with sources from like-oriented textures would answer several questions. Are vertical gratings processed in the same way as a dot pattern with strong vertical connectivity? The Campbell and Maffai work reviewed in Chapter II implied a definite correlation between the magnitude of VESP's for grating stimuli and the orientation of the gratings. Binocular stimulation with the stimulus to one eye ~~orthogonal~~ to the stimulus to the other eye was the means Campbell and Maffai used to obtain a response linked to the orthogonality of the stimuli. Rivalry and other problems of binocular interaction lead to some doubt about their conclusions unfortunately. If our technique is sensitive enough to discern variations in the VESP linked to the orientation and perhaps also the spatial frequency of bar stimuli, then a comparison could be made both with our own results for textures and with the single cell work with gratings.

If we can obtain localizations in our model head for the stimuli used in microelectrode experiments a direct anatomical analogy could be made. It is more likely that the solutions for bar stimuli will result in poorly localized sources which show little correspondence to those for the texture patterns. This conjecture is based on the fact that cells which the neurophysiologists have found respond well to bar stimuli are mainly located in visual area 17, an area that is for the most part buried within the calcarine fissure between the two occipital lobes in the human cortex.

Nevertheless, such a result would tell us that the cells responsible for the VESP's to textures (which are probably in the parastriate areas 18 and 19) are not very well tuned to grating patterns. This would mean the processing for gratings is probably located in a quite different population of cells from the one which handles textures.

Our conclusions concerning the relations of scalp potentials to perception suggest a strong role for these electrophysiological measures in the study of pattern vision. We have related the VESP to quite high-level perceptual tasks. It should be noted that the subject is probably not doing any high level perceptual things during the actual VESP recording sessions. Rather, the VESP's most likely arise from very repeatable primitive mechanisms which nevertheless form a critical part of the actual perception and discrimination tasks. Thus, measurement of VESP's might be used in experiments to determine automatically the nature of unknown patterns a subject is observing. Alternatively, when a subject is stimulated with known patterns, our VESP analysis could be used to estimate detection thresholds as well as the subject's confidence in judgements made verbally concerning the nature of the stimulus.

The work of Richards (1974) concerning the spatial frequency composition of one-dimensional textures also suggests further experiments with such stimuli. A consistent result for all subjects in our VESP analysis is the presence of variations in the source solutions as a function of the granularity quality of the stimulus. Richards' findings of primary spatial frequencies that can be mixed to match any one-dimensional texture of arbitrary frequency spectrum imply that these

primary frequencies define certain easily distinguished granularity levels. In other words, a texture constructed via the Richards' technique of adding random noise to a sinusoidal distribution of dots at one of the primary frequencies would be very easily distinguished from a texture centered at any of the other primary spatial frequencies. Thus, we might expect to localize the primary textures at quite different positions in our model head if our hypothesis that granularity is associated with the position of our source solutions holds true. We could then go further and study the relationship of the location of an arbitrary one-dimensional texture to the locations of the primaries. Perhaps the location of an arbitrary texture in our model could be predicted from psychophysical tests which give the relative weights of the primary textures required to produce a perceptual match to the given arbitrary texture.

Summary and Author's Absolution

It must be acknowledged that the thoughts expressed in this chapter are only suggested by the present experimental results. Having constructed such a fragile, delicately balanced set of hypotheses, the author is at pains not to enumerate the litany of their short comings lest they disintegrate before the ink is dried upon these lines. On the contrary, it seems appropriate that these ideas, the product of four years effort, be presented herein in as complimentary a light as possible. There is no doubt that they never again will appear as logical and profound as they do now at the moment of their conception. Ideas are worth nothing if their truths cannot be tested by the most uncompromising examiner. For certain, all the thoughts so bravely put forth here

are vulnerable to any number of experimental proofs. New ideas are the fuel for new experiments. If the thoughts expressed herein give rise to further experimentation on the VESP with multiple electrode arrays or in the area of texture perception, then they shall have more than served their purpose.

REFERENCES

- Armington, J. 1967. Variation of spontaneous ocular and occipital responses with stimulus patterns. J. Optical Soc. Amer. 57(12): 1534-1539.
- Armington, J. 1968. The electroretinogram, the visual evoked potential, and the area-luminance relation. Vision Res., 8: 263-276.
- Armington, J. 1971. Simultaneously recorded retinal and cortical responses to pattern stimuli. J. Optical Soc. of Amer., 61: 1514-1521.
- Armington, J. 1971. Electrophysiology of visual and perceptual activity. J. Psychiatric Res., 8: 309-322.
- Asher, H. 1951. The electroretinogram of the blind spot. J. Physiol., London, 112, 40P.
- Attneave, F. and R. K. Olson. 1967. Discriminability of stimuli varying in physical and retinal orientation. J. Exp. Psy., 14: 149.
- Barlow, H. B., R. Fitz Hugh, and S. W. Kuffler. 1957. Change of organization in the receptive fields of the cat's retina during dark adaptation. J. Physiol., 137: 338-354.
- Barlow, J. S. 1959. Autocorrelation and crosscorrelation analysis in electroencephalography. IRE Trans. Med. Electronics, ME-6: 179-183.
- Beck, J. 1972. Similarity grouping and peripheral discriminability under uncertainty. Amer. J. Psych., 85(1): 1-19.
- Blakemore, C. and F. W. Campbell. 1969. On the existence of neurones in the human visual system selectively sensitive to the orientation and size of retinal images. J. Physiol., 203: 237-260.
- Bourne, J. R., D. G. Childers and N. W. Perry. 1971. Topological characteristics of the visual evoked response in man. Electroenceph. Clin. Neurophysiol., 30: 423-436.
- Boynton, R. M. and L. A. Riggs. 1951. The effect of stimulus area and intensity upon the human retinal response. J. Exp. Psychol., 42: 217-226.
- Brazier, M. A. B. 1949. A study of the electrical fields at the surface of the head. Electroenceph. Clin. Neurophysiol., Suppl. 2, 38-52.

Brazier, M. A. B. 1958. Studies of evoked responses by flash in man and cat. In Reticular Formation of the Brain. Ed. Jasper, H. H., L. D. Proctor, R. S. Knightow, W. C. Moshay and T. T. Costello. Little, Brown, Boston.

Campbell, F. and L. Maffei. 1970. Electrophysiological evidence for the existence of orientation and size detectors in the human visual system. J. Physiol., 207: 635-652.

CIBA. 1958. Collection of Medical Illustrations. Vol. I: Nervous System. Prepared by Frank H. Netter, M.D. CIBA Pharmaceutical Products, Inc.

Cobb, W. and G. D. Dawson. 1956. The form and latency in man of the occipital potentials evoked by bright flashes. Intern. Physiol. Cong. 20th Cong. Abstr. Comm. 182.

Cobb, W. et al. 1967. Cerebral potentials evoked by pattern reversal and their suppression in visual rivalry. Nature, London 216: 1123-1125.

Cooley, W. W. and P. R. Lohnes. 1962. Multivariate Procedures for the Behavioral Sciences. New York.

Coombs, C. H. 1950. Psychological scaling without a unit of measurement. Psychol. Rev., 57: 145-158.

Coombs, C. H. 1958. An application of a non-metric model for multi-dimensional analysis of similarities. Psychol. Rep., 4: 511-518.

Coombs, C. H. and R. C. Kao. 1960. On a connection between factor analysis and multi-dimensional unfolding. Psychometrika, 25: 219-231.

Dawson, G. D. 1947. Cerebral responses to electrical stimulation of peripheral nerve in man. J. Neurol. Neurosurg. Psychiat., 10: 134-140.

Donchin, E. 1966. A multivariate approach to the analysis of average evoked potentials. IEEE Trans. Bio-Med. Engng. BME-13, 131-139.

Eccles, J. C. 1967. Circuits in the cerebellar control of movement. Proc. Nat. Acad. Sci., Washington. 58: 199-209.

Eccles, J. C., M. Ito and J. Szentagothai. 1967. The Cerebellum as a Neuronal Machine. Springer, Berlin.

Estrin, T. and R. Uzgalis. 1969. Computerized display of spatio-temporal EEG patterns. IEEE Trans. Bio-Med. Engng. BME-16: 162-196.

- Fender, D. and D. Lehmann. 1969. Fender-Lehmann electrode array shown in Scientific Res., April 28, 17.
- Fleming, D. E. and M. B. Canter. 1967. Perceptual responses and cortical potentials evoked in man by pulse trains of varied numbers and frequencies of presentation. Vision Res., 7: 611-617.
- Fourment, A., A. Jami, J. Carter and J. Sheiner. 1965. Comparaison de l'EEG recueilli sur le scalp avec l'activite elementaire des dipoles corticaux radiaires. Electroenceph. Clin. Neurophysiol., 19: 217-229.
- Frisch, H. L. and B. Julesz. 1966. Figure-ground perception and random geometry. Perception and Psychophysics. 1: 389-398.
- Fry, G. A. and S. H. Bartley. 1935. The relation of stray light in the eye to the retinal action potential. Amer. J. Physiol., 3: 335-340.
- Geisler, C. D. 1960. Average responses to clicks in man recorded by scalp electrodes. MIT Tech. Rep. No. 380.
- Green, B. F., A. K. Wolf, B. W. White. 1959. The detection of statistically defined patterns in a matrix of dots. Amer. J. Psych., 72(4): 503-520.
- Grossberg, S. 1970a. Some networks that can learn, remember, and reproduce any number of complicated space-time patterns, II. Studies in Applied Math., 49: 135-166.
- Grossberg, S. 1970b. Neural pattern discrimination. J. Theoret. Biol., 27: 291-337.
- Gubisch, R. 1967. Spatial resolution and interaction in human vision. Ph.D. Thesis, University of Cambridge, Mass.
- Halliday, A. M. and W. F. Michael. 1970. Changes in pattern-evoked responses in man associated with the vertical and horizontal meridians of the visual field. J. Physiol., 208: 499-513.
- Halliday, A. M., W. I. McDonald and J. Mushin. 1973. Visual evoked response in diagnosis of multiple sclerosis. British Med. J., 4: 661-664.
- Hammersley, J. M. 1950. The distribution of distances in a hemisphere. Ann. Math. Statist., 21: 447-452.
- Harman, H. H. 1960. Modern Factor Analysis. Chicago University Press.

Harter, M. R. and C. T. White. 1968. Effects of contour sharpness and check-size on visually evoked cortical potentials. Vision Res., 8: 701-711.

Hartline, H. K. 1938. The response of single optic nerve fibers of the vertebrate eye to illumination of the retina. Amer. J. Physiol., 121: 400-415.

Hartline, H. K. 1949. Inhibition of activity of visual receptors by illuminating nearby retinal areas in the Limulus eye. Fed. Proc. 8: 69.

Hays, W. L. and J. F. Bennett. 1961. Multi-dimensional unfolding: Determining configuration from complete rank order preference data. Psychometrika, 26: 221-238.

Hebb, D. O. 1949. The Organization of Behavior. New York, Wiley.

Henderson, C. J., S. R. Butler and A. Glass. 1975. The localization of equivalent dipoles of EEG sources by the application of electrical field theory. Electroenceph. Clin. Neurophysiol., 39: 117-130.

Hodgkin, A. L. 1951. The ionic basis of electrical activity in nerve and muscle. Biological Rev., 6: 339-409.

Hoek, L. D. van. 1974. Multivariate vectorial analysis of the visual evoked response. Kybernetik, 15: 65-72.

Hubel, D. H. and T. N. Wiesel. 1959. Receptive fields of single neurones in the cat's striate cortex. J. Physiol., 148: 574-591.

Hubel, D. H. and T. N. Wiesel. 1961. Receptive fields, binocular interaction, and functional architecture in the cat's visual cortex. J. Physiol., 160: 106-154.

Hubel, D. H. and T. N. Wiesel. 1964. Receptive fields and functional architecture in two non-striate visual areas (18 and 19) of the cat. J. Neurophysiol., 28: 229-289.

Jeffreys, D. A. 1971. Cortical source locations of pattern-related visual evoked potentials recorded from the human scalp. Nature, 229: 502-504.

Johnson, E. P., L. A. Riggs and A. M. L. Schick. 1966. Photopic retinal potentials evoked by phase alternation of a barred pattern. Vision Res. Suppl. 1, Clin. Electoretinography, 75-91.

Jones, L. A. and G. C. Higgins. 1945. The relationship between the granularity and graininess of developed photographic materials. J. Opt. Soc. Amer., 35: 455-457.

Julesz, B. 1962. Visual pattern discrimination. IRE Trans. of the Prof. Group on Information Theory, IT-8, No. 2, 84-92.

Julesz, B. 1965. Texture and visual perception. Sci. Amer., 212: 38-48.

Julesz, B. 1971. Foundations of Cyclopean Perception. Chicago: University Press.

Julesz, B. 1975. Experiments in the visual perception of texture. Sci. Amer., 232: 34-43.

Kavanagh, R. N. 1972. Localization of sources of human evoked responses. Ph.D. Thesis, California Institute of Technology, Pasadena, CA.

Kavanagh, R. N., Darcey, T. M., and Fender, D. H. 1976. The dimensionality of the human visual evoked scalp potential. Electroenceph. Clin. Neurophysiol. 40, 633-644.

Koffka, K. 1935. Principles of Gestalt Psychology. New York: Harcourt Brace.

Kooi, K. A. and T. Yamada. 1973. Field studies of monocularly evoked cerebral potentials in bitemporal hemianopsia. Neurology, 23: 1217.

Kruskal, J. 1964a. Multi-dimensional scaling by optimizing goodness of fit to a non-metric hypothesis. Psychometrika, 29(1): 1-27.

Kruskal, J. 1964b. Non-metric multi-dimensional scaling: A numerical method. Psychometrika, 29(2): 115-129.

Kruskal, J., F. Young and J. Seery. 1973. How to use KYST, a very flexible program to do multi-dimensional scaling and unfolding. Bell Lab. document, pp. 1-50.

Kuffler, S. W. 1953. Discharge patterns and functional organization of mammalian retina. J. Neurophysiol., 16: 37-68.

Lehmann, D., R. N. Kavanagh and D. H. Fender. 1969. Field studies of averaged visually evoked EEG potentials in a patient with a split chiasm. Electroenceph. Clin. Neurophysiol., 26: 193-199.

Lehmann, D. 1971. Multi-channel topography of human alpha EEG fields. Electroenceph. Clin. Neurophysiol., 31: 439-449.

- Lehmann, D. 1972. Human scalp EEG fields: Evoked, alpha, sleep, and spike-wave patterns. In: Synchronization of EEG activity in epilepsies. H. Petsche and M. A. B. Brazier, eds. Springer, pp. 307-326.
- Maffei, L. and A. Fiorentini. 1973. The visual cortex as a spatial frequency analyser. Vision Res., 13: 1255-1267.
- Mansfield, R. J. 1974. Neural basis of orientation perception in primate vision. Science, 186: 1133-1135.
- Marquardt, D. W. 1963. An algorithm for least squares estimation of nonlinear parameters. J. Soc. Industrial and Applied Math. II, No. 2, pp. 431-441.
- Marr, D. 1975. Analyzing natural images: A computation theory of texture vision. M.I.T. Artificial Intelligence Lab. Memo 334, pp. 1-43.
- Metzger, W. 1926. Reference in Gibson, J. J. 1950. The perception of the visual world. Boston: Houghton Mifflin, Co.
- Michael, W. F. and A. M. Halliday. 1971. Differences between the occipital distribution of upper and lower field pattern-evoked responses in man. Brain Res., 32: 311-324.
- Milner, B. A., D. Regan and J. R. Heron. 1974. Differential diagnosis of multiple sclerosis by visual evoked potential recording. Brain, 97: 755-772.
- Minkowski, M. 1913. Experimentelle Untersuchungen über die Beziehungen der Grosshirnrinde und der Netzhaut zu den drimären optischen Zentren, besonders zum corpus geniculatum externum. Arb. hirnanat. Inst., Zurich, 7: 259-362.
- Minsky, M. L. and S. Papert. 1969. Perceptrons: An Introduction to Computational Geometry. M.I.T. Press.
- Moskowitz, A. F., J. C. Armington and G. Timberlake. 1974. Corners, receptive fields, and visually evoked cortical potentials. Perc. and Psych., 15(2): 325-330.
- Nachimias, J., M. B. Sachs and J. G. Robson. 1969. Independent spatial frequency channels in human vision. J. Opt. Soc. Amer., 59: 1538.
- Offner, F. F. 1950. The EEG as potential mapping: The value of the average monopolar reference. Electroenceph. Clin. Neurophysiol., 2: 213-214.
- Papoulis, A. 1965. Probability, random variables, and stochastic processes. New York: McGraw-Hill.

Pettigrew, J. D., T. Nikara and P. O. Bishop. 1968. Binocular interaction on single units in cat striate cortex: Simultaneous stimulation by single moving slit with receptive fields in correspondence. Exp. Brain Res., 6: 391-410.

Plonsey, R. 1969. Bioelectric Phenomena. McGraw-Hill.

Pollen, D. A., J. R. Lee and J. H. Taylor. 1971. How does the striate cortex begin the reconstruction of the visual world? Science, 173: 74-77.

Pollen, D. A. and S. F. Ronner. 1975. Periodic excitability changes across the receptive fields of complex cells in the striate and parastriate cortex of the cat. J. Physiol., 245: 667-697.

Pribram, K. H. 1971. Languages of the Brain. Prentice-Hall.

Rall, W. 1969. Distributions of potential in cylindrical coordinates and time constants for a membrane cylinder. Biophys. J., 9: 1509-1541.

Ramon y Cajal, S. 1952. Histologie du systeme nerveux de l'homme et des vertebres. Madrid: Instituto Ramon y Cajal.

Regan, D. 1968. A high frequency mechanism which underlies visual evoked potentials. Electroenceph. Clin. Neurophysiol., 25: 231-237.

Regan, D. and W. A. Richards. 1971. Independence of evoked potentials and apparent size. Vision Res., 11: 43-56.

Regan, D. 1972. Evoked Potentials in Psychology, Sensory Physiology and Clinical Medicine. Chapman and Hall, Ltd., London.

Richards, W. and A. Polit. 1974. Texture matching. Kybernetik, 16: 155-162.

Rietveld, W., W. Tordior, J. Hagenouw, J. Lubbers and T. H. Spoor. 1967. Visual evoked responses to blank and to checkerboard patterned flashes. Acta Physiol. Pharmacol. Neurol., 14: 259-285.

Riggs, L. A., E. P. Johnson and A. M. L. Schick. 1966. Electrical responses of the human eye to changes in wavelength of the stimulating light. J. Opt. Soc. Amer., 56: 1621-1627.

Schneider, M. and P. Gerin. 1970. Une methode de localisation des dipoles cerebraux. Electroenceph. Clin. Neurophysiol., 28: 69-78.

Shaw, J. C. and M. Roth. 1955. Potential distribution analysis II. A theoretical consideration of its significance in terms of electric field theory. Electroenceph. Clin. Neurophysiol., 7: 285-292.

Shaw, J. C. and M. Roth. 1955. Potential Distribution Analysis I. A new technique for the analysis of electrophysiological phenomena. Electroenceph. Clin. Neurophysiol., 7: 273-284.

Shepard, R. 1962. The analysis of proximities: Multi-dimensional scaling with an unknown distance function I. Psychometrika, 27(2): 125-141.

Smythe, W. R. 1968. Static and Dynamic Electricity. McGraw-Hill, New York.

Spekreijse, H., L. H. Van der Tweel and D. Regan. 1972. Interocular sustained suppression: Correlations with evoked potential amplitude and distribution. Vision Res., 12: 521-526.

Spekreijse, H., L. H. Van der Tweel and Th. Zuidema. 1973. Contrast evoked responses in man. Vision Res., 13: 1577-1601.

Sutherland, N. S. 1968. Outline of a theory of visual pattern recognition in animals and in man. Proc. Roy. Soc. B., 171: 297-317.

Talbot, S. A. and W. H. Marshall. 1941. Physiological studies on neural mechanisms of visual localization and discrimination. Amer. J. Ophthal., 24: 1255-1263.

Taylor, M. M. 1963. J. Opt. Soc. Amer., 53: 763.

Tepas, D. I. and J. C. Armington. 1962. Properties of evoked visual potentials. Vision Res., 2: 449-461.

Torgerson, W. S. 1958. Theory and methods of scaling. New York: Wiley.

Tweel, L. H. Van der and H. Spekreijse. 1969. Signal transport and rectification in the human evoked response system. Ann. N. Y. Acad. Sci., 156: 678-695.

Van Hof, M. W. 1964. The influence of attention on the occipitocortical responses to light flashes in man. Documenta Ophth., 28: 238-244.

Vanzulli, A., J. Bogacz, P. Handler and E. Garcia-Austt. 1960. Evoked responses in man. Acta Neurol. Latinoamer., 6: 219-231.

Vaughn, H. G. 1966. The perceptual and physiologic significance of visual evoked responses recorded from the scalp in man. In: Clinical Electroretinography, Suppl. Vision Res., pp. 203-223.

Vaughan, H. G. and W. Ritter. 1969. The sources of auditory evoked responses recorded from the human scalp. Electroenceph. Clin. Neurophysiol., 28: 360-367.

Young, F. W. 1970. Non-metric multi-dimensional scaling: Recovery of metric information. Psychometrika, 35(4): 455-473.