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BIOCYBERNETIC CONTROL IN MAN-MACHINE INTERACTION

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This research program aims at incorporating EEG "evoked responses" in man-machine communication. Present work is toward developing a new model for the phenomena of evoked responses in the EEG based on sequential events of short duration in the bio-electric potentials.

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Current experiments use visual evoked responses using colored and patterne visual stimuli, void at first of any cognitive or emotional content. In the color experiments, both target and intensities in each color are varied separately. From the ensemble of these experiments, tentative candidate EEG codes have emerged that appear to reflect three retinal processes (red-green-blue). These are remarkable results since, while there is good evidence for a trichromatic absorbing structure in the fovea, there was no indication that these processes would be reflected into scalp potentials.

Topological Dimensionality studies showed that red and green components, although close in timing, did behave in a clearly distinct manner. In addition the response of the dark adapted eye, a limit case in background levels, was found clearly detached from the cluster in all cases. Simultaneously multichannel single epochs from the same experiments, have been analyzed off-line using stepwise discriminant analysis. The stimulus sets have proven extremely effective in providing on-line discrimination.

Data compression has been successfully achieved with the replacement of the single evoked response by the point processes formed by the peak instants in the positive or negative directions. This raises great hope that a combination of short event detection with amplitudes at selected times will provide encoding of the evoked response in a particularly economical manner in man-machine communication.

The experiments have raised continuous challenges to the computer system and required some additional developments. A "code cracking" software package has been successfully implemented on the IBM 360/91 at UCLA and will be accessible through the ARPANET.

The whole system has also been re-evaluated in view of its potential role in the program of data sharing and interconnection between Biocybernetic Laboratories. Special attention has been given to the articulation of the BCI software package with software resources at MIT-MULTICS.

Supportive work at the University of Iowa is also reported. At present, experimental work is directed at operant conditioning of the electroretinogram using rabbits as a preparation. Of direct interest is the conditionability of the B-wave or other components of the ERG that hinges on the existence and the function of centrifugal mechanisms capable of controlling some of the retinal processes.

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BIOCYBERNETIC CONTROL IN MAN-MACHINE INTERACTION:

TECHNICAL REPORTS NUMBER ONE

by

JACQUES J. VIDAL

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School of Engineering and Applied Science
University of California
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Short Title of Work:	Biocybernetic Control

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CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

SUMMARY

This is a research program that seeks to incorporate EEG "evoked responses" to complement overt behavior in specific man-machine communication schemes involving various aspects of decision making. Behind the experimental strategy is the view that the EEG in evoked responses is made up of a complex of wavelets that reflect individual and sequential events in the brain and in particular the cerebral cortex. The rules for appearance of these elementary wavelets would be the "syntactic" constraints upon a neuroelectric language with the wavelets acting as individual signatures for various aspects of the neural transactions that follow presentation of a stimulus. Once identified, the reliability and stability of those signatures can be reinforced naturally in the man-machine communication scheme, in a way amounting to operant conditioning. Thus the approach is centered on sequential events of short duration in bio-electric potentials and the relation between these sequences, behaviors and brain states. Those could in fact lead to a new model for the phenomena of evoked responses in the EEG.

Current experiments are aimed at visual evoked responses using colored and patterned visual stimuli, void at first of any cognitive or emotional content. Color flashes and patterns are choice stimuli that would provide potential support for non-verbal symbols in a man-machine communication language. In the color experiments, both target and intensities in each color are varied separately. From the ensemble of these experiments, tentative candidate EEG codes emerged that appear to reflect three retinal processes (red-green-blue). Best results have been obtained with a yellow background apparently because of the red-green depression caused by retinal adaption to yellow light. This allows the blue component, which had been elusive before, to appear much more clearly. These are remarkable results since, while there is good evidence for a trichromatic absorbing structure in the fovea, there was no indication that these processes would be reflected into scalp potentials.

Topological Dimensionality studies of the same data showed that red and green components, although close in timing, did behave in a clearly distinct manner. In addition the response of the dark adapted eye, a limit case in background levels, was found clearly detached from the cluster in all cases. Simultaneously multichannel single epochs from the same experiments, have been analyzed off-line using stepwise discriminant analysis with and without the detour of an orthogonal transformation. The results have been startling; the stimulus sets have proven extremely effective in providing a quality of discrimination that was unheard of with single EEG epochs, using only ten amplitude samples. Various representations were attempted, among which the replacement of the single evoked response by the point processes formed by the instants at which a single epoch was displaying a peak in the positive or negative direction. Cumulative histograms of those micro-events were found to be as stimulus-specific as are the averages, and it appears that some of the observed peaks correspond to the firing of specific nuclei. This raises great hope that a combination of short event detection with amplitudes at selected times will provide encoding of the evoked response in a particularly economical manner in man-machine communication. Already at this time, even without the benefit of amplitude information the peak "message" has equivalent clarity or discriminability, when compared to the peak histogram, than the single epoch with respect to the average.

The experiments have raised continuous challenges to the computer system and require additional developments. The central software package has been successfully implemented on the IBM 360/91 at UCLA and will be accessible through the ARPANET. It consists of a sequence of "code cracking" programs operating on epoch oriented data that will be ultimately used interactively. Several hardware improvements were made on the indigenous laboratory computers and the high-speed link that connects the laboratory to the 360/91. A tape drive and line printer controller were added to the SDS 920. Long vector hardware was successfully retrofitted on the IMLAC PDS-1 to allow

the creation of pattern stimuli under computer control.

Following recent directives, the whole system has been re-evaluated in view of its potential role in the program of data sharing and interconnection between Biocybernetic Laboratories. Special attention has been given to the articulation of the BCI software package with software resources at MIT-MULTICS. Finally a remote hardwired terminal connection between CCBS and BCI has been implemented and is now in operation.

Supportive work at the University of Iowa is also reported. At present, experimental work is directed at operant conditioning of the electroretinogram using rabbits as a preparation. Conditionability of the B-wave or other components of the ERG centers on the existence and the function of centrifugal mechanisms capable of controlling some of the retinal processes. Instrumentation as well as programming for on-line processing and stimulus presentation have been completed.

HUMAN EVOKED RESPONSE EXPERIMENTS-UCLA

In 1929 Berger demonstrated the possibility of recording brain waves from the intact skull. Since then, an enormous amount of brain wave data covering a variety of conditions has been accumulated by neurophysiologists, and in recent years, computers have been used extensively for analysis.

Overall characteristics of these fluctuations of electrical potential can be somewhat predicted in relation to the electrode site, the mental state of the subject, and the presence and type of sensory stimulation. Some of those characteristics are readily identified by eye. Well-known examples are recognition of alpha activity and the phenomenon of alpha blocking, sleep and barbituate spindles, and the 3-per-second spike and wave complex of petit mal epilepsy. More subtle information in the EEG signals, however, requires computer analysis.

This "spontaneous" or "on-going" electrical activity is somewhat rhythmic in nature. The analysis of these rhythms has retained much of the early attention paid to brain waves in general. Yet it is increasingly evident that rhythmic activities contain little information in themselves and that their function is probably similar to that of a carrier. The general picture is that idle nervous tissue will exhibit spontaneous oscillation or rhythm while activity or commitment of the same tissue to an active function will be denoted by desynchronized random-like oscillations.

Beyond gross differentiation of brain states, it seems that information coding in the EEG wave should be sought in the specific waveforms generated in time. By contrast with the wide spread character of oscillations, the wave shapes obtained with "evoked potential" are localized and correspond well with underlying post-synaptic potentials. Evoked potentials (evoked responses) are generally obtained with a light flash, brief sound, or touch of the skin which generates in the corresponding sensory cortex (visual, auditory or somesthetic), a localized electrical response in the form of an aperiodic waveform lasting up to half a second and superimposed on the ongoing background activity. In general, repeated stimuli and averaging of the waveforms have been used to reveal the "evoked" response by cancelling the background "noise".

Indeed early investigations in 1965 by Fox and O'Brien resulted in the demonstration that stimulus-evoked potentials were directly related to the probability of firing of any particular cell in the area of population included in the brain wave recording. Specifically, the studies showed that in these cortical cells, the probability of firing could be described almost precisely by the shape of the slow wave associated with that same electrode. Thus, the relationship between single-cell spikes and evoked potential was dramatically clarified.

Fox and Norman demonstrated that the spike-wave relationship would also hold for spontaneous activity of the cortex. The next step then was to determine if these potentials might represent behavior, based on these earlier studies which showed that the

moment-to-moment changes in amplitude and polarity of the slow activity of the brain represented moment-to-moment changes in probability of firing of single cells.

To achieve this took a novel approach. Fox and Rudell for the first time used operant reinforcement techniques to increase or decrease the probability of occurrence of some component of the visual evoked potential. This they claimed was tantamount to asking the animal whether, under reinforcement control, it could increase or decrease the probability of some aspect of his brain wave. In turn this was equivalent to asking whether or not the animal had any behavior available for reinforcement, which utilizes, encodes or is represented by the particular aspect of brain activity chosen.

To pursue the study of this brain-behavior relationship to time-dependent behaviors, Rosenfeld and Fox trained unrestrained cats with implanted electrodes to make discrete paw movements. At the same time the mixed sensory-motor potential was recorded in the cortex. These data, treated correlatively, showed a relationship of early waves and early portions of each movement and of later waves and later portions of each movement, but relative independence of early and late measurements.

In the second part of these experiments a particular aspect of the movement-evoked potential in the cortex was chosen and by reinforcement control, the animals were trained to increase the probability or amplitude of this particular component of the brain wave. Exactly in accordance with prediction, the animals, when

this training was accomplished, altered some aspect of their limb movements. To the discrete changes of the cortical evoked potential associated with movement, corresponded some discrete and finely detailed changes in some aspects of the movement of the limb, showing that spontaneous activity of the brain from moment-to-moment encodes function and the sequential probabilities of single-cell firing were functionally represented by the sequential and momentary changes in brain waves. More important, moment-to-moment changes in behavior were discretely reflected in moment-to-moment changes in sequential brain waves.

These findings in animal studies are very significant insofar as they point out the functional meaning of the "gross" EEG potentials generated by populations rather than single neurons. In other words, at least in some conditions, the neural "roar" does not cancel out into hopeless noise. With humans and without implanted electrodes, the difficulties are certainly compounded. But in compensation more avenues are open for operant conditioning, a technique that may well be the key to success in identifying the EEG "codes".

A starting point in this study was the recognition that different stimuli with specific set of features evoke distinguishable electrical "signatures" on the scalp. For instance, the response to the brief flashing of a figure made of vertical lines will yield a waveform markedly different from that obtained from a set of circles. In fact, the presence in the evoked waveforms of clear correlates of the modalities of sensory stimulation has been abundantly demonstrated.

Of particular interest are studies dealing with visual stimuli (White and Eason, 1966; Harter and White, 1968, 1969; Clynes and Kohn, 1967; Rietveld, et al, 1967; Spehlmann, 1965; Spekreise, 1966). The evoked electrical signature on the cortex does however include more than a mirror conversion of the stimulus content. In fact only the early part of the response appears to be directly stimulus bound, while the "late" components appear to relate to more complex brain functions related to the stimulus such as its perception and meaning.

The general approach was defined as follows in the original proposal: First, stimulus sets are selected that span some "dimensions" expected to elicit neural correlates, that is, changes in evoked response. Next, wave components in the neural response are identified that appear to correlate with each stimulus dimension, thus providing a first identification of the "candidate" code, along with its sensitivity and stability. In this phase the model-free topological dimensionality analysis is applied to the data to reveal its parametric dimensionality in relation to each stimulus dimension. Outcome "candidate" waveforms or parameters are then isolated and compared from subject to subject. For each subject the reliability and stability of the emerging dimensions must be evaluated in repeated experiments. As the initial bioelectric configuration emerges from dimensionality analysis, an interactive closed loop mode is entered. Operant conditioning techniques are applied to individualize and sharpen these waveforms.

Current experiments are aimed at the conditioning of selected attributes of visual evoked responses and are using colored and patterned visual stimuli, (void at first of any cognitive or emotional content). Color flashes and patterns are choice stimuli that would provide potential support for non-verbal symbols in a man-machine communication language. Eventually the cognitive or emotional content of the stimulus was to be considered (e.g. whether the subject has directed his attention towards a specific feature in the complex stimulus, or whether the occurrence of the stimulus represents a gain or a loss in a game playing situation--or whether the stimulus is varied in a dimension varying from pleasant to aversive). These extensions were to be attempted at the end of the second year and would continue throughout the third year.

This calendar is being followed. The bulk of experiments has been conducted with colored flashes and more recently patterns, that is, stimuli that are at the same time dimensionally rich and structurally simple.

A brief review of the basic laws of color vision will be given next as an introduction to the experiments on evoked response to color.

TRICHROMATICITY

The essential trichromaticity of color vision has been demonstrated by the results of color mixing experiments using the most powerful psychophysical technique for making color judgment, which is to use the eye as a null instrument. Any spectral color can be matched by the proper mixture of any three colors, providing that none of the colors chosen as primaries can be made by mixing the other two. No matter what three colors are chosen as primaries, however, it will always be necessary to assign a negative coefficient to one of them

i.e. add some of it to the match in order to bring it within reach of the given 3-color system. Red, green and blue are usually chosen as primaries because a wider range of colors can be made using only positive coefficients. In mathematical terms, if X is any color, and A, B, and C are primaries, then we can always find coefficients a, b, and c such the X = aA + bB + cC. Furthermore, if we make another color Y with different amounts of the same primaries, Y = a'A + b'B + c'C, then it turns out that the mixture of the two lights X and Y to make color Z is obtained by taking the sum of the components of X and Y:

$$Z = X + Y = (a + a')A + (b + b')B + (c + c')C.$$

So the laws of color mixture are just like the mathematics of the addition of vectors. Represent everything on a plane by reducing all colors to the same intensity making a + b + c = 1, to get the standard chromaticity diagram, Fig. 8.1

It follows that the color obtained by mixing a given two will be somewhere on a straight line connecting the two points, for example a fifty-fifty mixture would appear halfway between them, and so on. If we use blue, green, and red as primaries then all the colors that can be made with positive coefficients will lie inside the dotted triangle. The curved boundary line is the locus of the pure spectral colors, and the area within this boundary contains all the colors that can be made with lights, with white at the center. The colors outside the boundary cannot be made with lights, and are never seen, except perhaps in after-images.

The simplest theory of the mechanism of color vision, proposed by Young and Helmholtz, postulates that there are exactly three different receptor pigments in the eye, which respond maximally to, say, red,

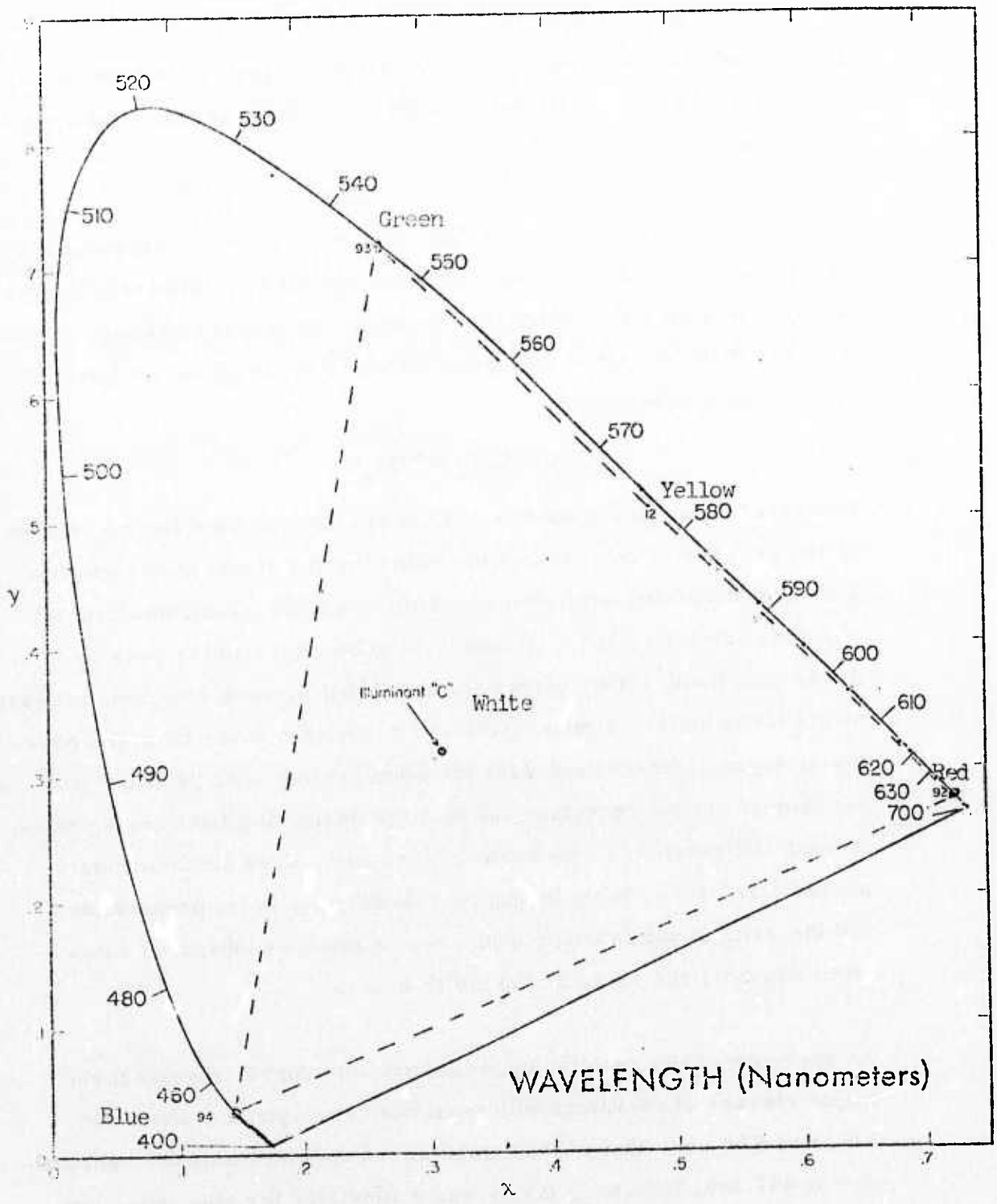


Figure 1

Chromaticity diagram for Standard Source "C" (artificial daylight). This shows the colors of various Kodak filters when they are illuminated by the Standard Source "C" specified by the International Commission on Illumination (CIE). This Standard Source "C" is approximately equivalent to average daylight, having a color temperature of 6750 K.

green, and blue wavelengths. These three channels of information are then processed somehow by the visual system so that colors can be perceived.

The laws of color mixing can be demonstrated to be a consequence of this proposition, but since we can make any kind of linear transformation of the color coordinates that we want, we cannot determine uniquely what the three receptor absorption curves are simply on the basis of color mixing experiments.

COLOR RECEPTORS

For several decades a number of workers have focused their attention on the problem of determining the nature of the visual photopigments. The most definitive data has come from the microspectrophotometry of Marks, Dobelle, and MacNichol, in 1964, and similar work by Brown and Wald, 1964. Marks et. al. (1964) present data from measurements taken on ten primate cones and two human cones from the parafoveal region. Their procedure included the use of an "end-on" preparation of retinal receptors, so that the measuring light beam passed through the receptor in the normal direction. They simultaneously passed a reference beam through a "blank" spot in the preparation, and the ratio of the intensity of the two beams was measured automatically over the range of 390 nm to 670 nm.

An overview of the results, including primate cones, reveals three major classes of receptors with maximum absorption at about 445, 535, and 570 nm. One of the human cones showed maximum absorption at 457 nm, indicating that it was a mediator for blue sensation. The other human cone tested by Marks, et. al. (1964) was probably a red receptor, with its peak absorption at 575 nm.

The absorption difference spectra from the majority of the "red" cones showed a secondary hump or peak near 555 nm suggesting the possibility that single "red" receptors may contain red and green pigments, coexisting in a single cone.

Brown and Wald (1964) measured the difference spectra of 4 human cones using a similar "end-on" preparation from the parafoveal region of the retina. Their technique differed from Marks, et.al. (1964) in that they took a difference spectrum, i.e., they obtained the absorption spectrum, then bleached the receptors with a bright flash of light and obtained a bleached absorption spectrum. The difference between the unbleached and bleached absorption spectra is the difference spectra. Brown and Wald's data represent one blue receptor, two green-receptors, and one red receptor. The peaks in these curves fell at about 450, 525, and 555 nm. The blue-receptor peak of 450 nm agrees well with Marks et.al. blue receptor which peaked at 457 nm, but the gree and red-receptor peaks seem to occur at somewhat shorter wavelenghts than was found earlier by Brown and Wald when relatively large patches of human fovea were measured.

TETRACHROMATICITY

It is often stated that there are four "psychologically unique" colors; red, yellow, green and blue. These lead to the so-called opponent-color theories, such as those proposed by Hurvich and Jameson (1955). The blue, green and yellow primaries are also special in that they do not undergo a Bezold-Brucke shift; that is, their hue is invariant with changes in luminance. Psychometric experiments show red and green as antagonistic colors; their mixture, yellow, is not perceived by subjects as either red nor green. Conversely, blue and yellow lights mix to form white. Hurvich and Jameson (1955) have worked out

a formal mathematical theory, based on the opponent-color hypothesis, with which they are able to match predicted and experimental data quite well for various phenomena, including the Bezold-Brucke shift, wavelength discrimination, spectral saturation, and color mixture. These results are not surprising since their chromatic response functions are linear transformations of the CIE mixture curves with the addition of four "variable constants" which are manipulated for best fit.

Color theory is still evolving, and it was felt that this was an area in which evoked response studies could make an important contribution. This choice provided an extremely fortunate collaboration with Dr. C.T. White at NEL. Indeed, his preliminary data indicated that a paradigm of this type would be a very rich vein for our purpose. A sample of that preliminary data is shown in Fig. 8.2. There, average evoked responses are shown to red, green and blue flashes presented against yellow backgrounds. Background level on the one hand and stimulus intensities in each color on the other hand, were varied separately. From the ensemble of these experiments obtained under different background colors and intensities, tentative candidate codes emerged that accounted for the three hypothetical processes (at retinal level) corresponding to the red-green-blue trichromatic theory (Fig. 8.3). The yellow background was thought to produce particularly representative evoked responses because of the red-green depression caused by retinal adaption to yellow light. This allows the blue component, which had been elusive before, to appear much more clearly. These were startling results since, while there is good evidence for a trichromatic absorbing structure in the fovea (Fig. 8.4) there was no indication that these processes would be reflected into scalp potentials (collected in the occipital area). This finding also brings as a next question, the potential role of the opponent color theory developed from psychophysical

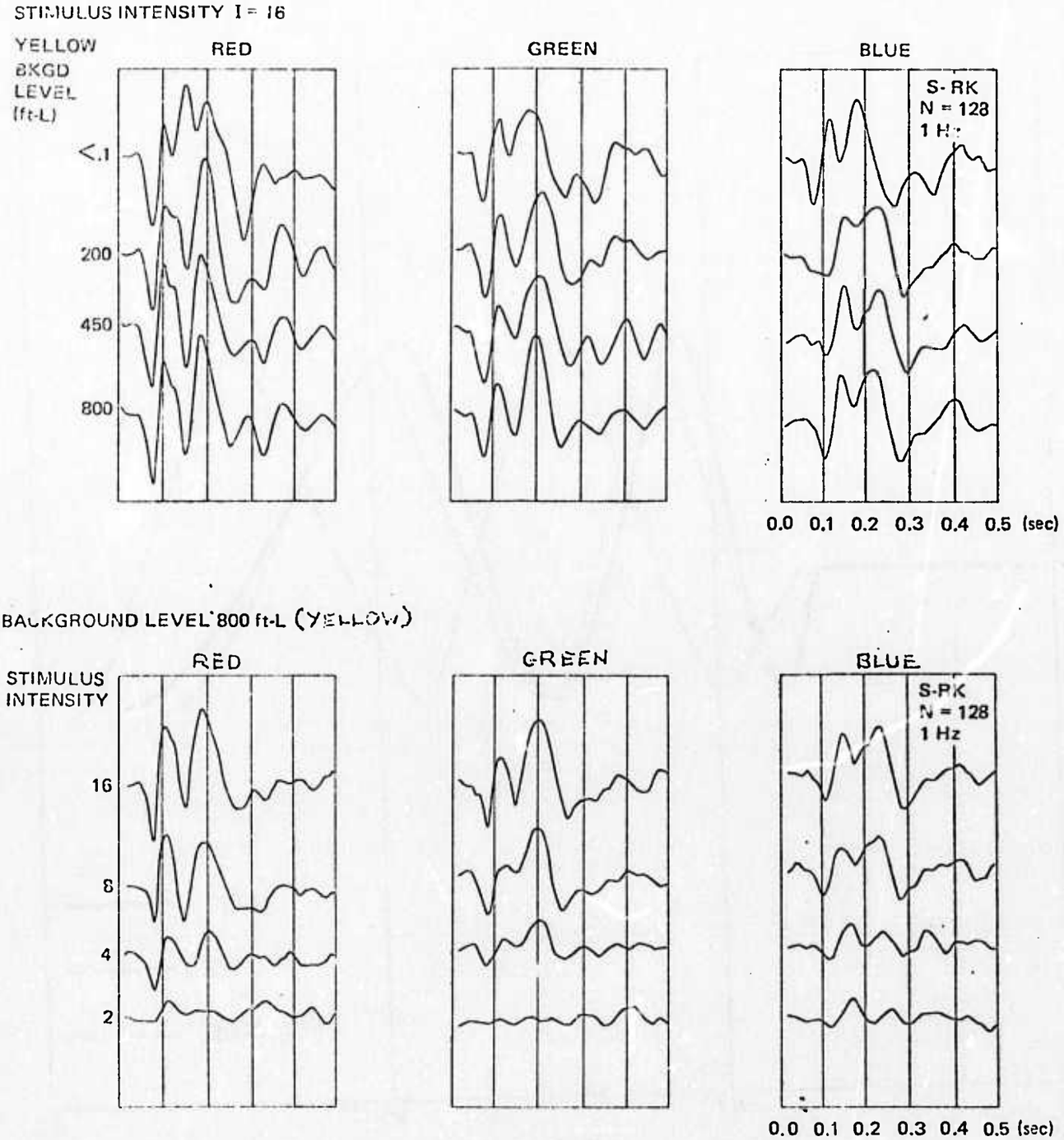

STIMULUS INTENSITY I = 16
YELLOW BKGD LEVEL (ft-L)
RED
GREEN
BLUE
S-RK
N = 128
1 Hz
<.1
200
450
800
0.0 0.1 0.2 0.3 0.4 0.5 (sec)
BACKGROUND LEVEL 800 ft-L (YELLOW)
STIMULUS INTENSITY
RED
GREEN
BLUE
S-RK
N = 128
1 Hz
16
8
4
2
0.0 0.1 0.2 0.3 0.4 0.5 (sec)

Figure 2

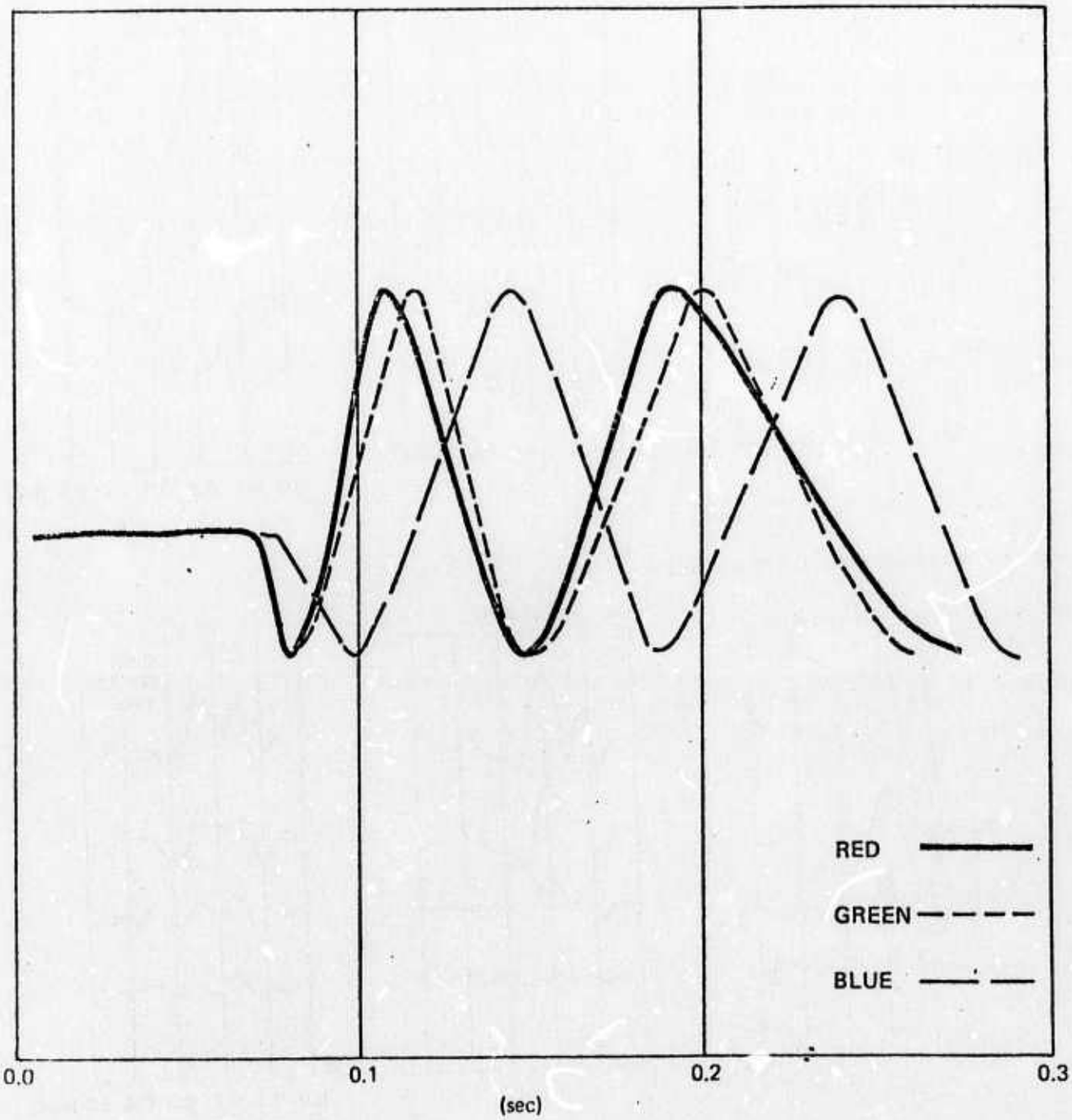
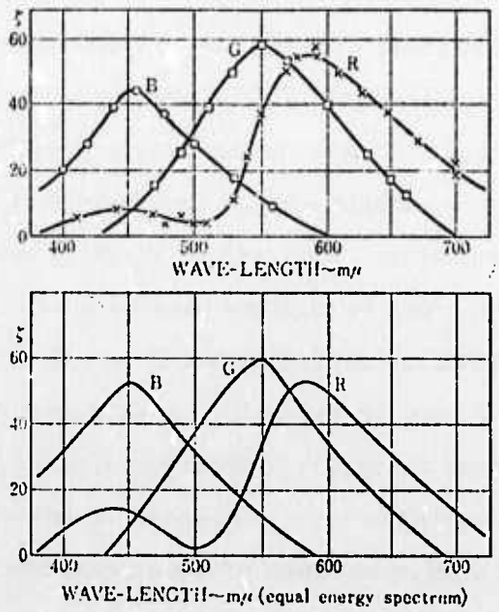


Figure 3



Curves showing dependence of magnitudes of the three basic retinal processes upon wavelengths of spectral lights, obtained from fovea of normal trichromat. (MOTOKAWA, 1949.)

Figure 4

experiments.

Topological Dimensionality studies of this early data showed that red and green components, although very close in timing, did behave in a clearly distinct and quasi-orthogonal manner with respect to each other when background or stimulus intensities were changed (Fig. 5). The response of the dark adapted eye, a limit case in the background level series, clearly detached itself from the cluster in all cases. A fraction of this preliminary data was obtained at NEL without the benefit of automatic data acquisition and digitizing systems. Thus, single epochs had been lost and only graphic averages were available. Analysis of these is now pursued using a borrowed graph pen to digitize plotted data. Since then, the experiments have been conducted at the Brain Computer Interface Laboratory and have been or are being analyzed through the BCI software package without resorting to averaging (except for the final displays). Twelve subjects have been evaluated on the basis of evoked response quality and relative absence of muscle artifacts and five are presently retained. The BCI experiments are focused on single epochs (averages are actually irrelevant to the Biocybernetic goals.)

Meanwhile, on-line experiments are being pursued to further probe the fine structure of the EEG epochs and search for better primitives than amplitude samples. Particularly intriguing was the possibility that by adequate representation of the data, these primitives could be made explicit. Various representations were attempted, among which the replacement of the single evoked response by the point processes formed by the instants at which a single epoch was displaying a peak in the positive or negative direction (Fig. 6). In other words, the series of zero crossing instants for the first derivative of the amplitude function together with the sign of the second derivative. Cumulative

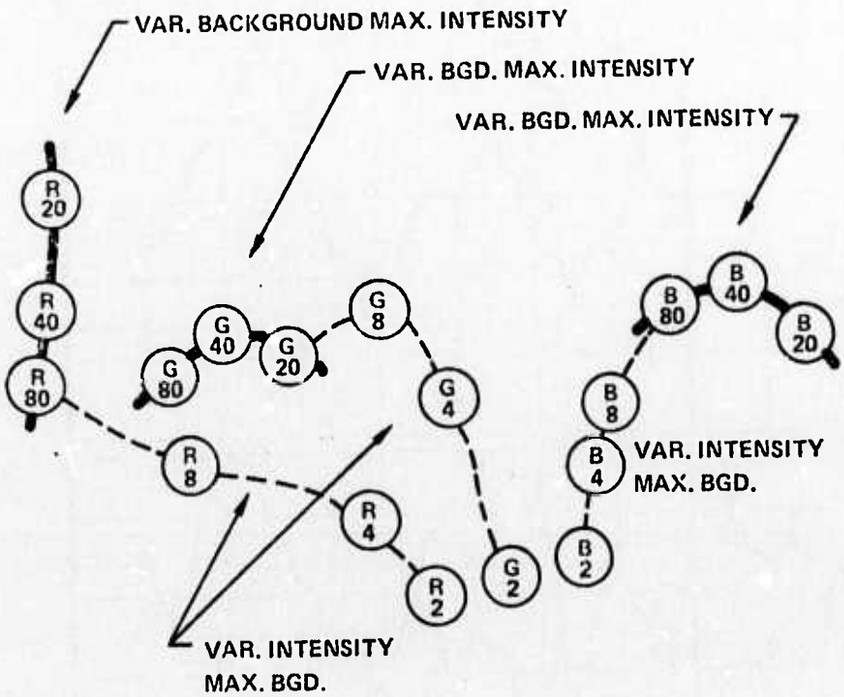
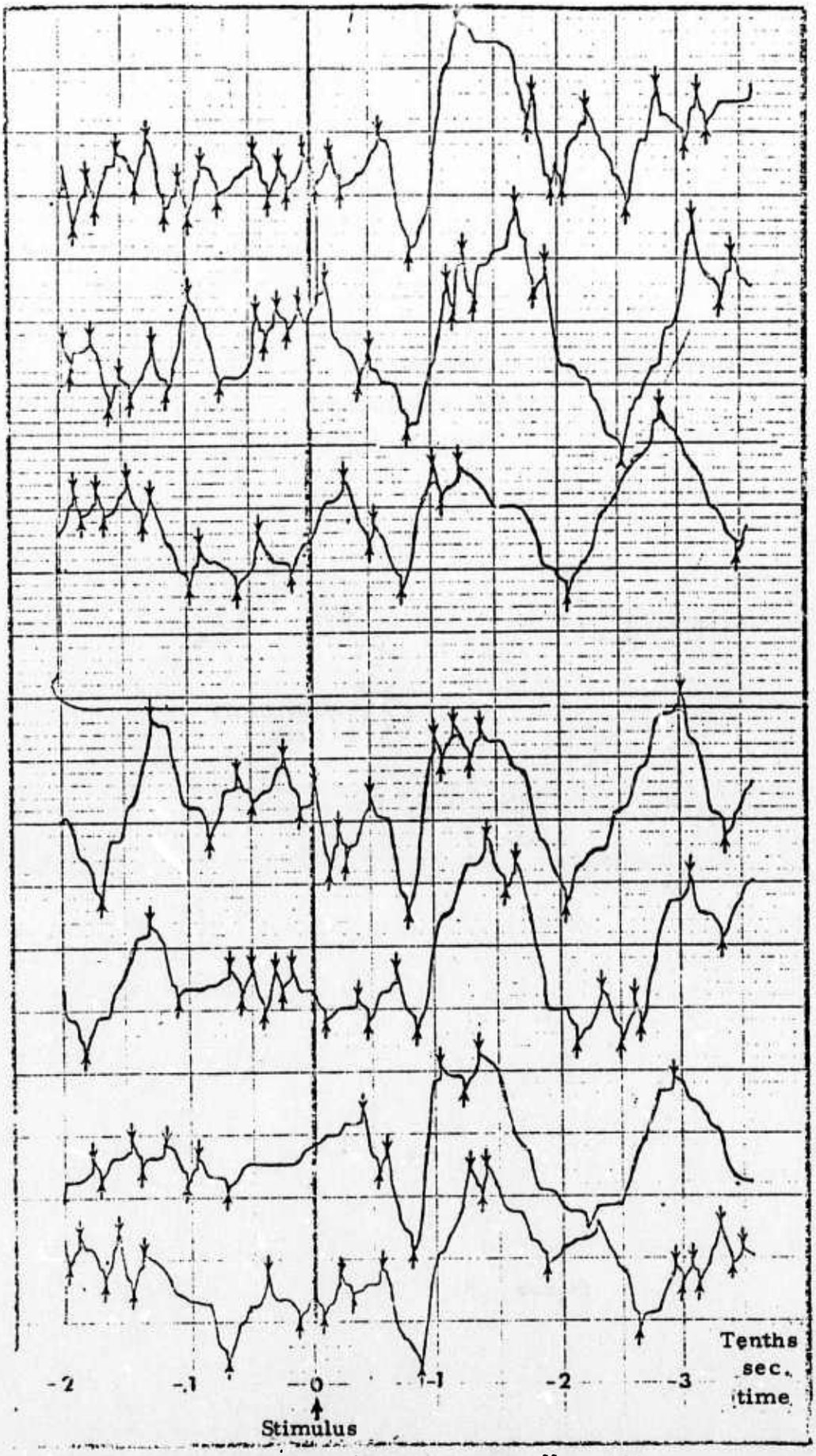

VAR. BACKGROUND MAX. INTENSITY
VAR. BGD. MAX. INTENSITY
VAR. BGD. MAX. INTENSITY
R 20
R 40
R 80
R 8
R 4
R 2
G 80
G 40
G 20
G 8
G 4
G 2
B 80
B 40
B 20
B 8
B 4
B 2
VAR. INTENSITY MAX. BGD.
VAR. INTENSITY MAX. BGD.

Figure 5



Single Epochs CP Red 3/Background Yellow 100

Figure 6

histograms of those micro-events were obtained and compared to the averages (Fig. 7). These histograms were found to be as stimulus-specific as are the averages. While the relationship between the histograms and the underlying slow wave, can be explained to some extent by the procedure itself (i.e. the "bunching" of the peaks by the slow wave), it has already been established that the stability and sharpness of some of the peaks could not be explained if the small peaks were just high frequency noise. Rather it appears that the slow wave conjugates with short events which may correspond to the firing of specific nuclei. This raises great hope that a combination of short event detection with amplitudes at selected times will provide encoding of the evoked response in a particularly economical manner in man-machine communication. Already at this time, even without the benefit of amplitude information the peak "message" has equivalent clarity or discriminability, when compared to the peak histogram, as the single epoch has with respect to the average.

A next move is underway to investigate the possibility that the peak set or some variation of it contains identifiable moment-to-moment information. Operant conditioning techniques are expected to provide some of the answers and various operant paradigms are being evaluated. Present results are still at a level of casual observations. Fig. 8 for example, shows a run in which the reward (a conditioning) was attached to the presence of small positive peaks in the vicinity of 300 milliseconds. The growth of the amplitude of this component in the average is clearly seen in the graph.

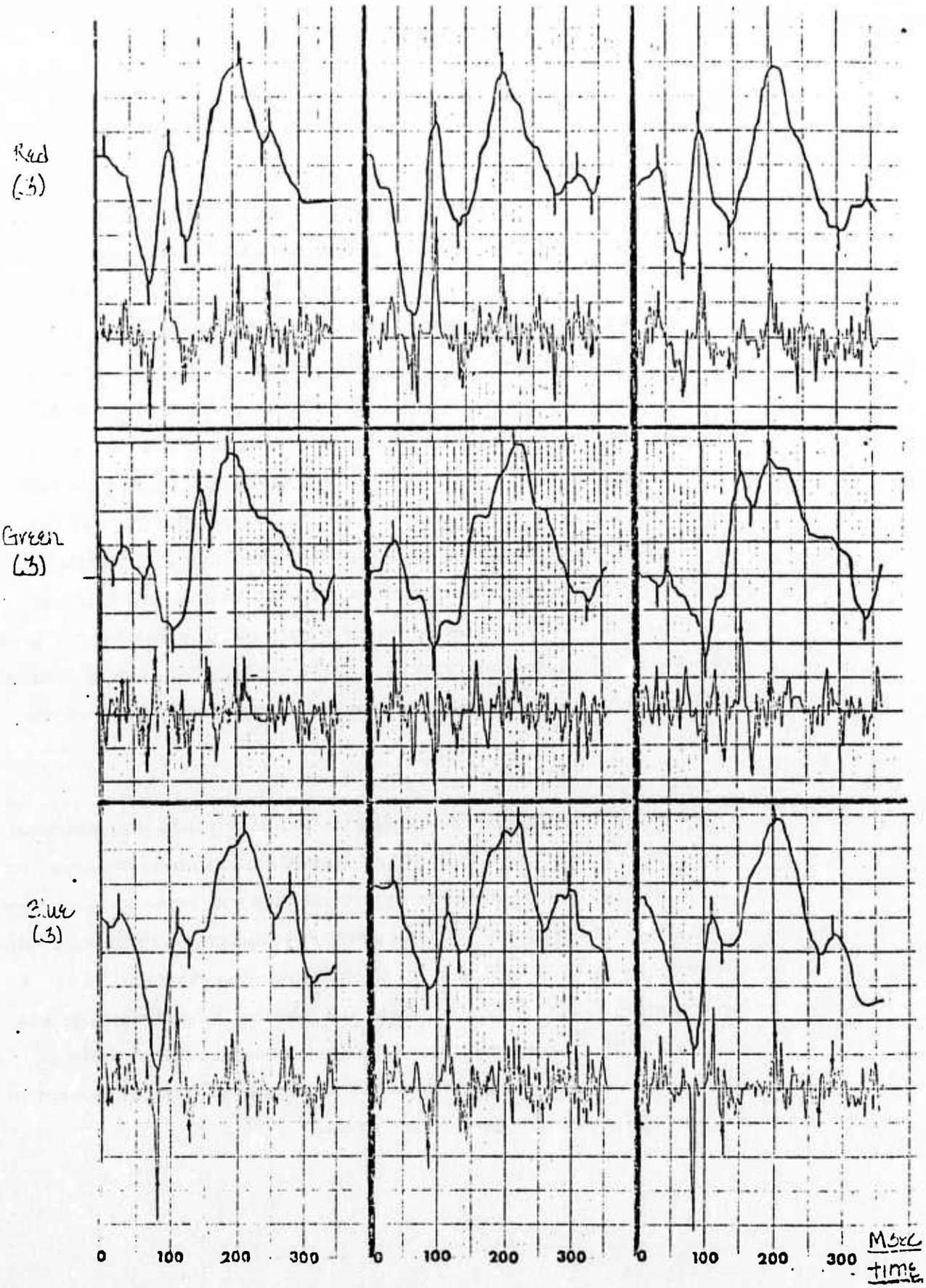


Figure 7

Amplitude Averages & Peak Histograms

(TB, N=30, BGD=Yellow 100)

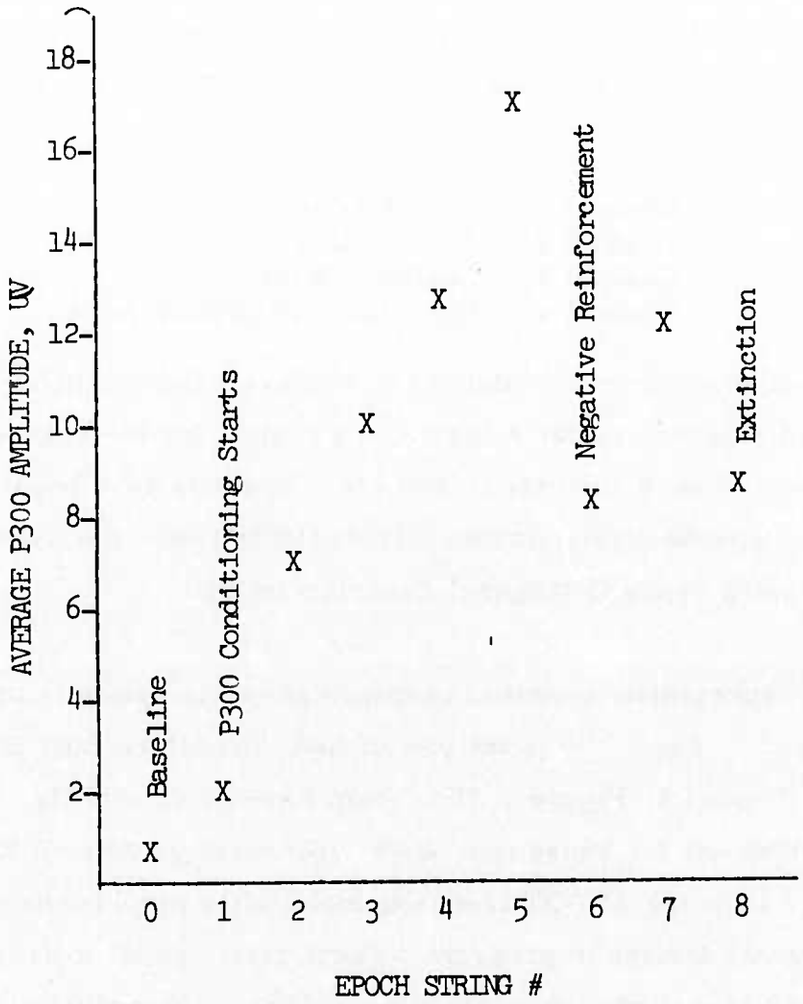

AVERAGE P300 AMPLITUDE, UV
18
16
14
12
10
8
6
4
2
Baseline
P300 Conditioning Starts
Negative Reinforcement
Extinction
0 1 2 3 4 5 6 7 8
EPOCH STRING #

FIGURE 8

Data from one subject whose Evoked Potentials (EVPOTS) were extensively studied is presented next. This experiment consisted of 48 presentations of a flash of colored light of either red, green, or blue hue, over a yellow background. The brain electrical activity was sampled for 5 seconds prior to and 320 milliseconds following each flash, from four electrode locations. Electrodes were placed as follows:

Channel 1	Frontal/Ears
Channel 2	Vertex/Ears
Channel 3	Occipital/Ears
Channel 4	(Eye) Inferior Orbital/Ears

This experiment is not intended to represent the definitive color evoked response study; rather it is a vehicle for the evaluation of evoked response analysis techniques. The data have been analysed using stepwise discriminant analysis (SWDA) with and without preprocessing by the Orthogonal Transformation.

Some representative evoked response plots are shown in the following figures. Fig. 9 in the plot of Red, Green and Blue EVPOTS from Channel 1, Figure 10 is from Channel 2, and Fig. 11 is from Channel 3. These are "RAW" (non-orthogonalized) EVPOTS. Fig. 12 is the EVPOT from Channel 2 after preprocessing by the orthogonal derivation program. These plots are all average EVPOTS from 48 epochs of each of the three colors. The ordinate is in microvolts, positive up, the abscissa is time; there are 80 samples spaced 4 msec. apart. The flash occurred at time point 1.

Clearly, the average EVPOTS evoked by the different colors look different, but we need a measure of how different they are, with a nice regard for the variability from trial to trial. The stepwise discriminant analysis (SWDA) program does provide an objective measure

Data from one subject whose Evoked Potentials (EVPOTS) were extensively studied is presented next. This experiment consisted of 48 presentations of a flash of colored light of either red, green, or blue hue, over a yellow background. The brain electrical activity was sampled for 5 seconds prior to and 320 milliseconds following each flash, from four electrode locations. Electrodes were placed as follows:

Channel 1	Frontal/Ears
Channel 2	Vertex/Ears
Channel 3	Occipital/Ears
Channel 4	(Eye) Inferior Orbital/Ears

This experiment is not intended to represent the definitive color evoked response study; rather it is a vehicle for the evaluation of evoked response analysis techniques. The data have been analysed using stepwise discriminant analysis (SWDA) with and without preprocessing by the Orthogonal Transformation.

Some representative evoked response plots are shown in the following figures. Fig. 9 in the plot of Red, Green and Blue EVPOTS from Channel 1, Figure 10 is from Channel 2, and Fig. 11 is from Channel 3. These are "RAW" (non-orthogonalized) EVPOTS. Fig. 12 is the EVPOT from Channel 2 after preprocessing by the orthogonal derivation program. These plots are all average EVPOTS from 48 epochs of each of the three colors. The ordinate is in microvolts, positive up, the abscissa is time; there are 80 samples spaced 4 msec. apart. The flash occurred at time point 1.

Clearly, the average EVPOTS evoked by the different colors look different, but we need a measure of how different they are, with a nice regard for the variability from trial to trial. The stepwise discriminant analysis (SWDA) program does provide an objective measure

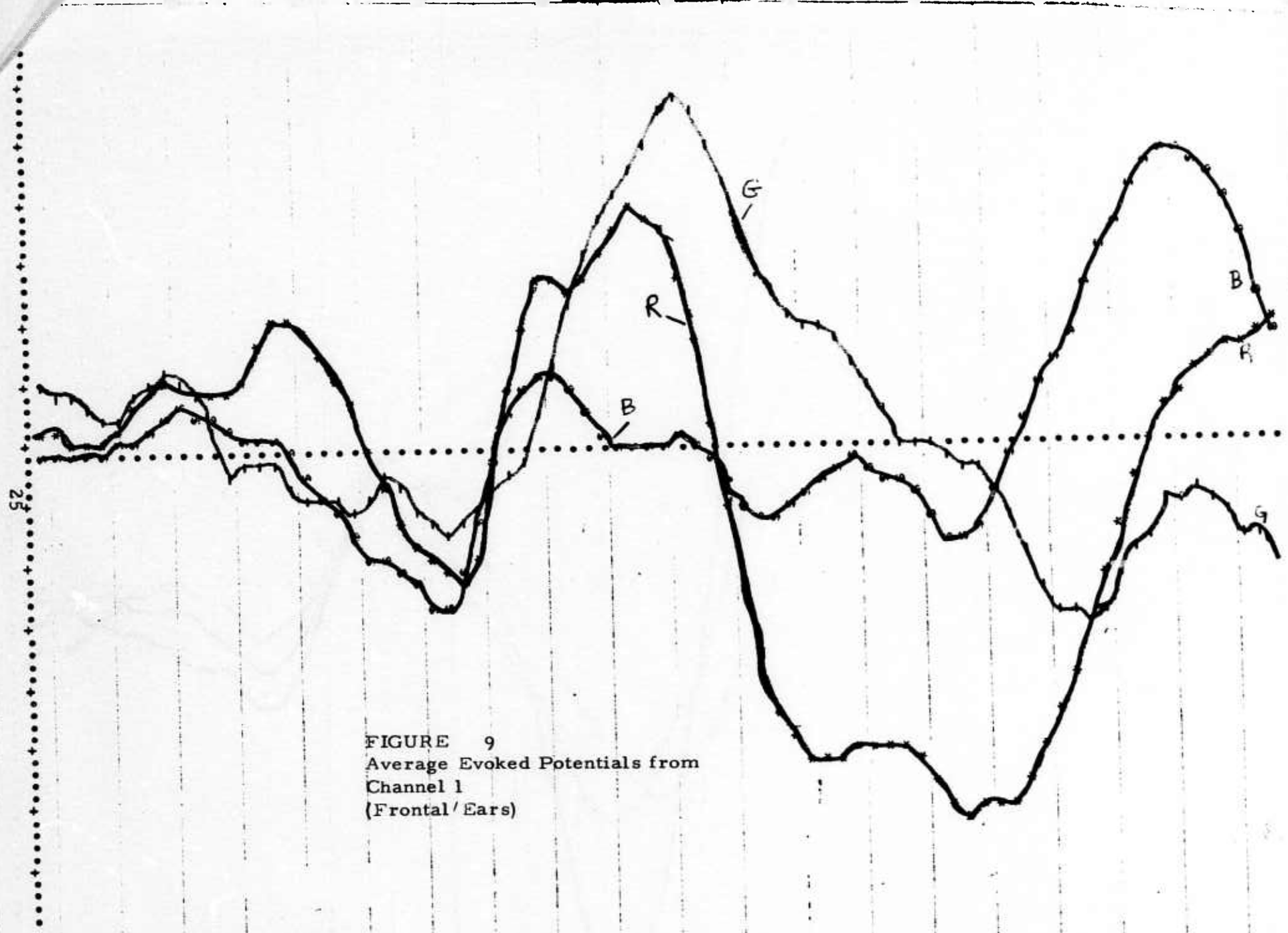


FIGURE 9
Average Evoked Potentials from
Channel 1
(Frontal/Ears)

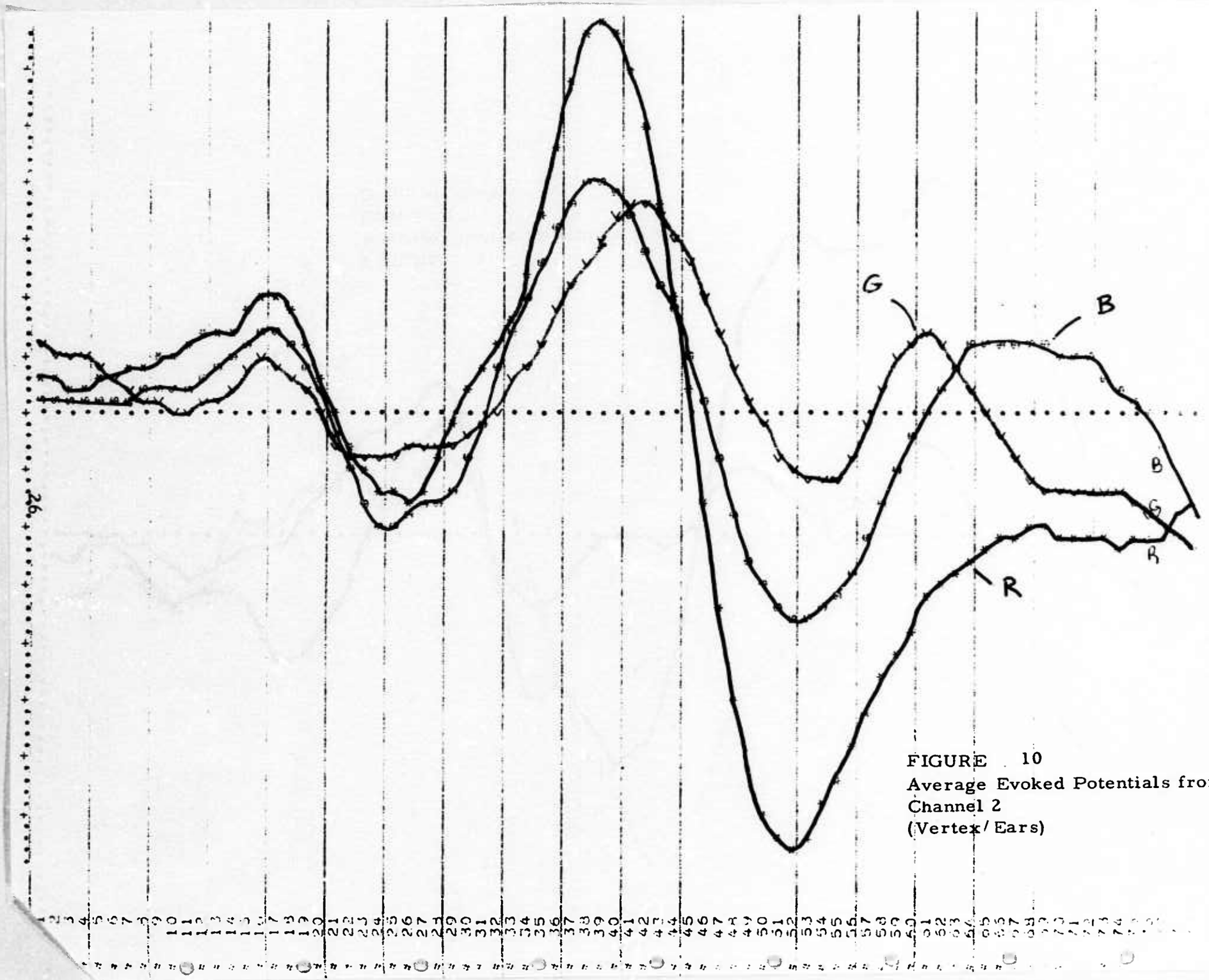


FIGURE 10
Average Evoked Potentials from Channel 2
(Vertex/Ears)

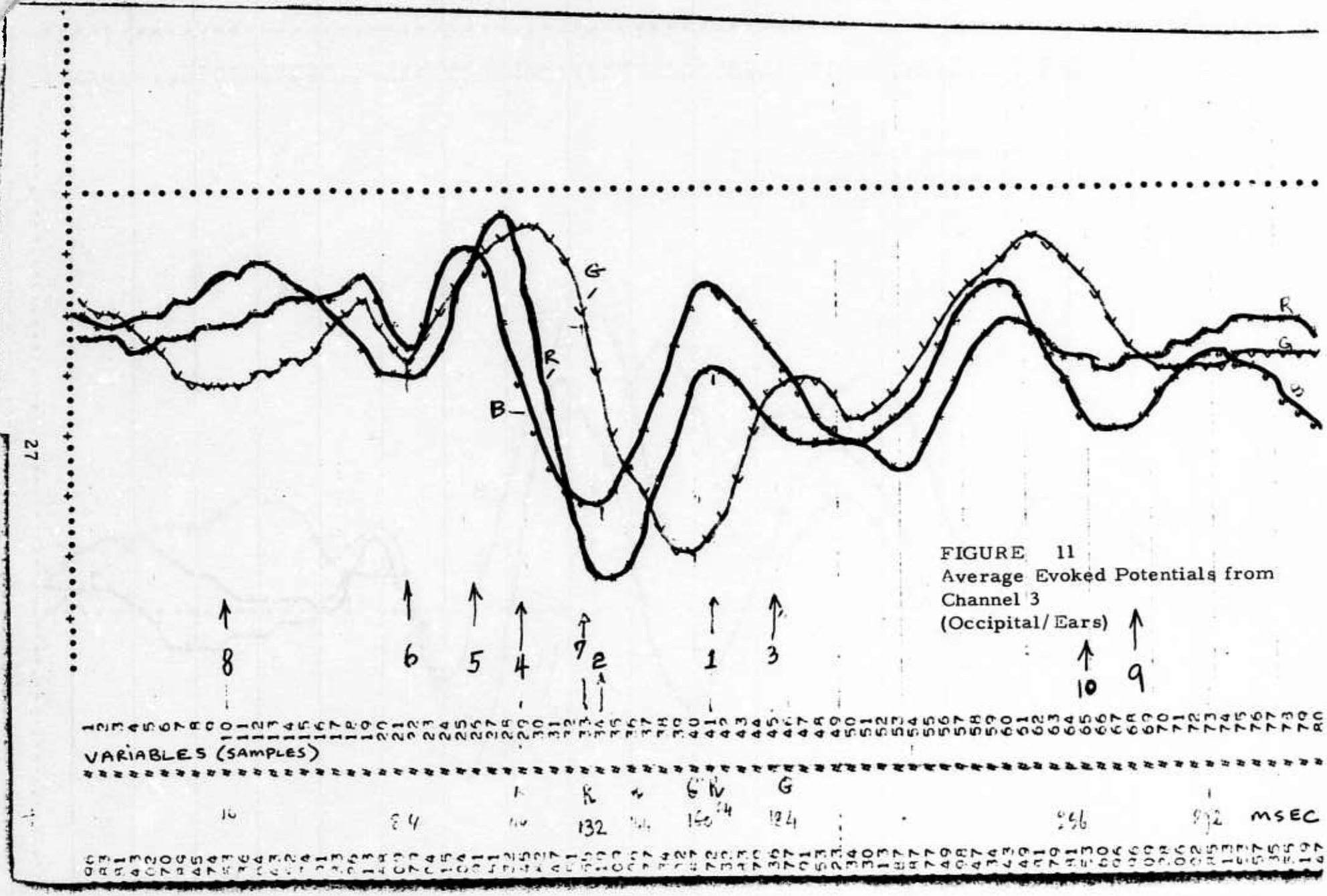


FIGURE 11
Average Evoked Potentials from Channel 3
(Occipital/Ears)

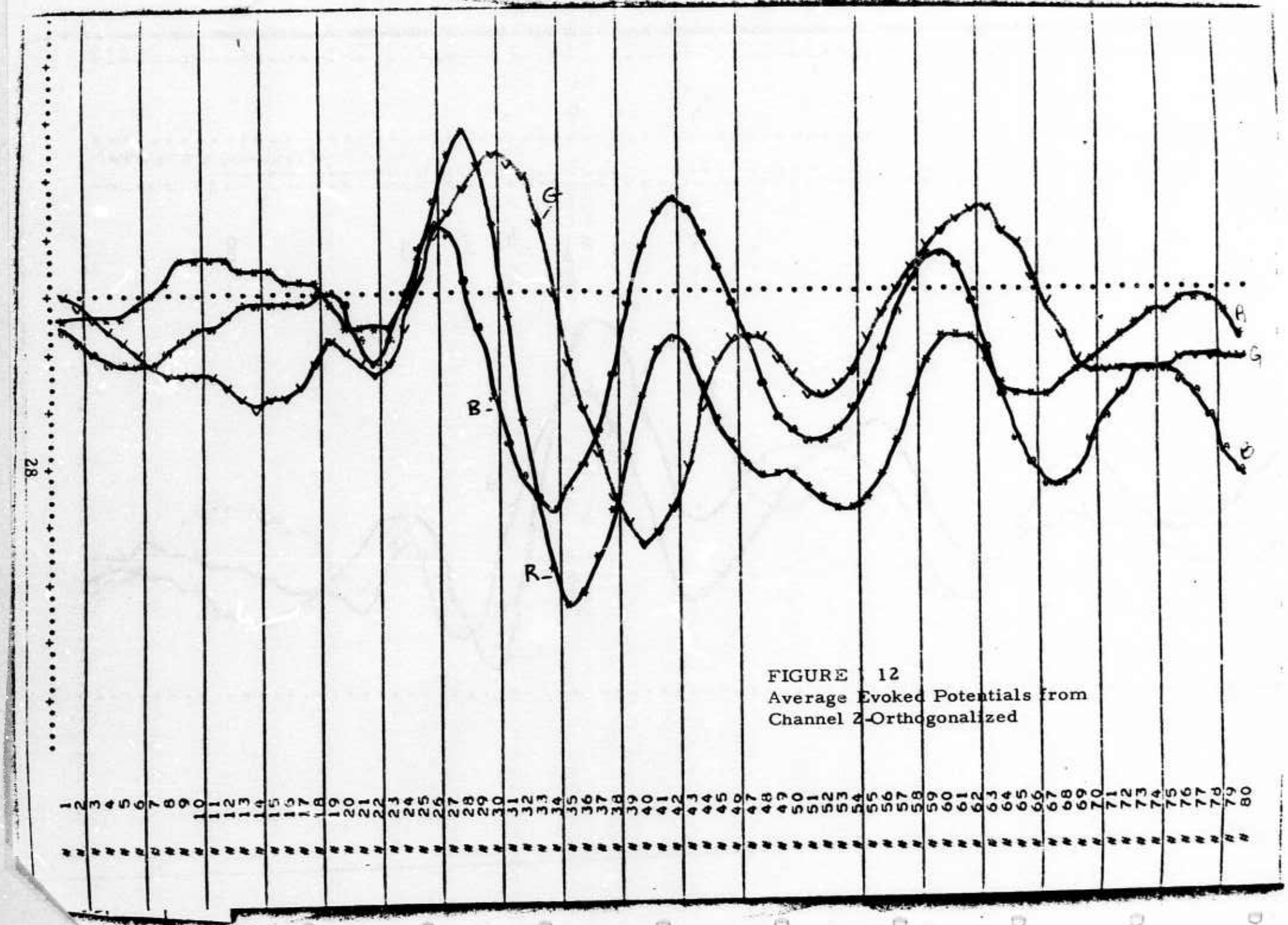


FIGURE 12
Average Evoked Potentials from
Channel 2-Orthogonalized

of the differences between these multivariate distributions , based on the variability and the regularity in the data.

The program computes a set of linear classification functions by choosing a subset of the original 80 variables in a stepwise manner. The variable entered at each step is selected according to one of four possible criteria; typically that variable will be chosen which has the largest F-to-enter. The F statistic which is computed at each step gives us an indication of the differences between groups relative to the differences within groups.

Typically, the SWDA program is told to select the 10 best variables, then it computes the coefficients of these variables which produces the best possible discrimination between groups, and prints a classification matrix. Each case (epoch) is evaluated using the discriminant function (D.F.) developed and its posterior probability of belonging to each group (color) is computed as well as the square of the Mahalanobis distance from each group.

The program also computes the coefficients for canonical variables and plots the first two canonical variables to give an optimal two-dimensional picture of the separation of groups.

Other measures generated by SWDA include group means and standard deviations, within groups covariance matrix, the within groups correlation matrix; and for each step, the variables included and F-to-remove, variables not included and F-to-enter , Wilk's Lambda (or U statistic) and approximate F statistic to test equality of group means, and the matrix of F statistics to test the equality of means between each pair of groups.

A subset of this wealth of information about the data has been tabulated and will be referred to in the following paragraphs, along with comments about its significance.

Referring to the map distances in table 1, it is seen that blue and red are the closest pair in ch. 3 and ch. 3 ORTHO (over visual cortex) while blue and green are closest for ch. 4 and ch. 4 ORTHO.

This finding, if further validated, may be the first demonstration of an objective measure of cortical processing of hue information in intact man. Furthermore, such a finding would be predicted by the retinal pigment curves of Motokawa (1949) which show blue and red to be at the two extremes of the spectrum, thus least similar, as is found in ch. 4 (eye). Also, the nearness of blue and red over visual cortex (ch. 3) matches the data in the CIE chromaticity diagram, (Fig. 1) which was constructed from psychophysical experiments, thus reflecting the process occurring in visual cortex.

Also from Table 1, referring to the 10 step classification matrices, it can be seen that SWDA did a very good job of classifying each epoch into its proper group, using a D.F. based on only 10 sample variables. Ch. 3 RAW gave the most accurate classification, with an error rate of 7.6% when operating with three groups, and ch. 2 ORTHO wasn't far behind, with a misclassification rate of 8.9%. The classification matrix also provides distance information in the form of confusability. Looking at the 10 step matrix for 3 colors, for ch. 3 RAW (Table 1), it is seen that green epochs are always classified as belonging to the green group, 48 out of 48, while 44 red epochs were correctly classified as red, none as green, and 4 were classified as blue. Also, 7 epochs of blue were incorrectly classified as red, none as green, and

TABLE # 1

RUN #	CHANNEL, RAW OR ORTHO DATA DESCRIPTION	GROUP NAMES GR 1 vs GR 2	MAP DISTANCE (INCHES)	GROUP	CLASSIFICATION MATRICES								
					STEP 1			STEP 5			STEP 10		
					Red	Grn	Blu	Red	Grn	Blu	Red	Grn	Blu
1	Channel 1 Raw	Red vs Grn	4.10	Red	32	9	7	36	3	9	35	4	9
		Red vs Blue	2.30	Grn	8	34	6	5	36	7	4	42	2
		Grn vs Blue	3.25	Blu	22	19	6	7	7	33	8	3	36
2	Channel 1 Ortho	Red vs Grn	3.40	Red	41	7	0	43	2	3	45	1	2
		Red vs Blue	3.50	Grn	8	9	31	3	39	6	2	36	10
		Grn vs Blue	1.50	Blu	6	14	29	2	7	40	0	4	45
3	Channel 2 Raw	Red vs Grn	4.30	Red	30	4	14	34	3	11	41	3	4
		Red vs Blue	3.15	Grn	3	32	13	2	39	7	3	41	4
		Grn vs Blue	2.80	Blu	13	16	18	11	8	28	4	7	36
4	Channel 2 Ortho	Red vs Grn	3.90	Red	17	15	16	40	1	7	42	0	6
		Red vs Blue	1.65	Grn	14	33	1	1	47	0	1	47	0
		Grn vs Blue	3.90	Blu	9	5	35	0	1	42	6	0	43
5	Channel 3 Raw	Red vs Grn	5.10	Red	17	12	19	41	0	7	44	0	4
		Red vs Blue	3.50	Grn	11	36	1	1	46	1	0	48	0
		Grn vs Blue	5.00	Blu	9	3	35	5	1	41	7	0	40

RUN #	CHANNEL, RAW OR ORTHO	GROUP NAMES	MAP DISTANCE	GROUP	STEP 1			STEP 5			STEP 10		
6	Channel 3 Ortho	Red vs Grn	2.85	Red	32	3	13	32	2	8	40	3	5
		Red vs Blue	2.10	Grn	4	29	15	3	42	3	2	42	4
		Grn vs Blue	2.60	Blu	11	19	19	10	3	36	5	6	38
7	Channel 4 Raw	Red vs Grn	4.10	Red	43	5	0	45	0	3	45	1	2
		Red vs Blue	4.90	Grn	7	17	24	2	38	8	1	41	6
		Grn vs Blue	2.50	Blu	5	19	23	2	8	37	1	5	41
8	Channel 4 Ortho	Red vs Grn	3.00	Red	26	9	13	39	1	8	41	0	7
		Red vs Blue	2.10	Grn	4	30	14	2	39	7	1	41	6
		Grn vs Blue	1.50	Blu	16	16	17	9	12	28	4	3	37
					RED	NON RED		RED	NON RED		RED	NON RED	
9	Channel 1 Ortho (Red vs Non Red)	Red vs Non Red	3.50	Red	33	15		43	5		46	2	
				Non-Red	7	90		2	95		2	95	
10	Channel 3 Raw (Red vs Non Red)	Red vs Non Red	3.10	Red	23	25		45	3		45	3	
				Non-Red	9	86		11	84		6	89	
					GRN	NON GRN		GRN	NON GRN		GRN	NON GRN	
11	Channel 1 Ortho (Grn vs Non Grn)	Grn vs Non Grn	2.50	Grn	18	30		36	12		36	12	
				Non-Grn	15	82		10	87		7	90	
12	Channel 3 Raw (Grn vs Non Grn)	Grn vs Non Grn	4.30	Grn	32	16		48	0		48	0	
				Non-Grn	10	85		0	95		0	95	

Table 1 cont.

RUN #	CHANNEL, RAW OR ORTHO	GROUP NAMES	MAP DISTANCE	GROUP	STEP 1		STEP 5		STEP 10	
					BLU	NON BLU	BLU	NON BLU	BLU	NON BLU
13	Channel 1 Ortho (Blu vs Non Blu)	Blue vs Non Blue	2.70	Blu	21	28	41	8	41	8
				Non-Blu	8	88	9	87	10	86
14	Channel 3 Raw (Blu vs Non Blu)	Blue vs Non Blue	4.10	Blu	30	17	36	11	42	5
				Non-Blu	14	82	6	90	2	94
					RED	GRN	RED	GRN	RED	GRN
15	Channel 1 Ortho (Red vs Grn)	Red vs Grn	3.90	Red	40	8	46	2	48	0
				Grn	7	41	2	46	1	47
16	Channel 3 Raw (Red vs Grn)	Red vs Grn	4.30	Red	38	10	48	0	48	0
				Grn	10	38	1	47	0	48
					RED	BLU	RED	BLU	RED	BLU
17	Channel 1 Ortho (Red vs Blue)	Red vs Blue	3.90	Red	42	6	44	4	46	2
				Blu	5	44	2	47	1	48
18	Channel 3 Raw (Red vs Blue)	Red vs Blue	3.70	Red	33	15	44	4	48	0
				Blu	18	29	6	41	2	45
					GRN	BLU	GRN	BLU	GRN	BLU
19	Channel 1 Ortho (Green vs Blue)	Grn vs Blue	2.90	Grn	29	19	41	7	43	5
				Blu	17	32	6	43	2	47
20	Channel 3 Raw (Green vs Blue)	Grn vs Blue	4.30	Grn	42	6	48	0	48	0
				Blu	7	40	0	47	0	47

Table 1 cont.

40 were correctly placed in the blue column. These results imply that red and blue are closer than either red and green or blue and green in these data, since they are more often confused, i.e. incorrectly classified as each other by the program.

A. CHANNEL WISE: COMPARISONS (TABLE 2)

1) As expected, with the raw data, channel 3 gave the best discrimination followed by channels 4, 2 and 1 respectively.

2) Channels 1 and 2 chose similar initial variables to discriminate between the different color groups.

3) The time points around 12, 26, 30, 33, 41, 45, 65 and 69 seemed to predominate the classification functions computed for the various channels from the raw data.

B. DATA WISE (RAW VS. ORTHO): (TABLE 2)

1) The orthogonal data gave the best discrimination in channel 2 followed by channels 1, 3 and 4 respectively.

2) Interestingly, the variables chosen by the program for channel 1 (ORTHO) were very different from those chosen for channel 1 (RAW). This was unexpected as channel 1, being the base channel was not to go through any change during orthogonalization, but was band-pass filtered. This effect, however, has improved the discrimination power of the channel.

3) The appreciable deterioration in the discriminative capabilities of channels 3 and 4 tells us of a need for the verification of the process of orthogonalizing. There is a clear need for a test of the orthogonal transformation using synthetic data with known parameters. Such a test is now being devised.

4) The time points around 10, 20, 29, 33, 35 and 41 are predominant in the classification functions chosen for the orthogonalized data.

CHANNEL WISE COMPARISONS TABLE # 2

*** Indicates 90.0% or over

RUN #	DATA DESCRIPTION	GROUPS/# CASES	CORRECT CLASSIFICATION PERCENTAGE ACHIEVED	# STEPS	VARIABLES CHOSEN (AFTER 10 STEPS)
	(Red vs Grn vs Blue)				
1	Channel 1 Raw	Red/48 vs Grn/48 vs Blue/47	81.1	9	50, 69, 61, 41, 32, 30, 20, 36 4, 40
2	Channel 1 Ortho	Red/48 vs Grn/48 vs Blue/49	88.2	8	21, 44, 14, 10, 5, 12, 29, 27, 32, 8
3	Channel 2 Raw	Red/48 vs Grn/48 vs Blue/47	82.5	10	50, 40, 69, 61, 36, 30, 44, 74, 65, 80
4	Channel 2 Ortho	Red/48 vs Grn/48 vs Blue/47	***	8	41, 35, 46, 30, 10, 28, 69, 58, 71, 66
5	Channel 3 Raw	Red/48 vs Grn/48 vs Blue/47	***	5	41, 34, 45, 29, 26, 22, 33, 10, 68, 65
6	Channel 3 Ortho	Red/48 vs Grn/48 vs Blue/49	83.4	8	51, 33, 42, 27, 46, 76, 32, 26 29, 30
7	Channel 4 Raw	Red/48 vs Grn/48 vs Blue/47	***	12	20, 44, 13, 9, 32, 26, 29, 4, 12, 48
8	Channel 4 Ortho	Red/48 vs Grn/48 vs Blue/47	82.0	10	37, 34, 31, 40, 19, 77, 35, 29, 18, 25

C. COLOR WISE COMPARISONS:

I. RED: (Table 3 runs #9, 10; Table 4 runs #15-18)

1) Red color data is easily separable.
2) Using the channel 1 ORTHO runs (#9, 15, 17) we see that time points around: 5, 10, 12, 14, 21, 27, 29, 48 and 62 dominate.
3) Using the channel 3 RAW runs (#10, 16, 18) we see that time points around: 21, 29, 33, 36, 46 predominate.
4) We also note that time point 29 occurs in all the six runs indicating that time point 29 definitely is associated with a red color component.
5) Overall, time points 21, 29 and 33 can be attributed to the color Red.

II. GREEN: (Table 3 runs #11, 12; Table 4 runs #17-20)

1) Green color seems to be easily distinguishable by SWDA
2) Using channel 1 ORTHO runs (#11, 17, 19) we see ;that time points around: 5, 9, 13, 17, 27, 28, 32, 38, 43 dominate.
3) Using channel 3 RAW runs (#12, 18, 20) we see that time points around: 10, 20, 28, 41, 45, 64, 73 seem to dominate.
4) Overall, time points 28, 45 could be attributed to the Green color

III. BLUE: (Table 3 runs #13-14; Table 4 runs #13-16, 19-20)

1) Using the channel 1 ORTHO runs we find that time points around: 5, 9, 11, 13, 22, 27, 29, 38, 56 seem to dominate.
2) Using the channel 3 RAW runs we find that time points around: 18, 21, 22, 24, 33, 37, 41, 79 seem to dominate.
3) Time point 22, 38 could be attributed to Blue color.

COLOR WISE COMPARISONS TABLE # 3

*** Indicates 90.0% or over

RUN #	DATA DESCRIPTION	GROUPS/# CASES	CORRECT CLASSIFICATION PERCENTAGE ACHIEVED	# STEPS	VARIABLES CHOSEN (AFTER 10 STEPS)
9	Channel 1 Ortho (Red vs Grn & Blue)	Red/48 vs Non Red/97	***	2	21, 48, 14, 29, 27, 31, 4, 12, 11, 62
10	Channel 3 Raw (Red vs Grn & Blue)	Red/48 vs Non Red/95	***	4	34, 29, 33, 26, 69, 38, 55, 51, 47, 36
11	Channel 1 Ortho (Grn vs Red & Blue)	Grn/48 vs Non Grn/97	87.5	7	44, 17, 9, 13, 5, 28, 32, 27, 38, 37
12	Channel 3 Raw (Grn vs Red & Blue)	Grn/48 vs Non Grn/95	***	2	41, 34, 45, 10, 73, 64, 37, 20, 33, 28
13	Channel 1 Ortho (Blue vs Red & Grn)	Blu/49 vs Non Blu/96	***	6	26, 14, 9, 32, 5, 23, 25, 56, 38, 42
14	Channel 3 Raw (Blu vs Red & Grn)	Blu/47 vs Non Blu/96	***	6	40, 30, 26, 67, 33, 22, 38, 24, 21

D. INTER COLOR QUALIFICATIONS

I. RED vs GREEN: (Tables 3 and 4 runs #9-12, 17-18)

1) Using channel 1 ORTHO runs (9, 11, 17) we see that time points around: 5, 10, 12, 21, 29, 32, 43, 62 dominate.

2) Using channel 3 RAW runs (10, 12, 18) we see that time points around: 10,20, 29, 33, 34, 36, 40, 64, 73 dominate.

II. GREEN vs. BLUE: (Tables 3 and 4 runs # 11-14, 19-20)

1) Using channel 1 ORTHO runs (11, 13, 19) we see that time points around: 5, 9, 13, 17, 27, 32, 38, 56 dominate.

2) Using channel 3 RAW runs (12, 14, 20) we see that time points around: 10, 20, 33, 34, 37, 41, 45, 64 dominate.

III. RED vs. BLUE: (Tables 3 and 4 runs #9, 10, 13-16)

1) Using channel 1 ORTHO runs (9, 13, 15) we find that time points around: 5, 9, 12, 14, 22, 27, 29, 48 dominate

2) Using channel 3 RAW runs (10, 14, 16) we find that time points around: 20, 26, 29, 33, 34 dominate.

To answer the question as to how good the classification functions produced by SWDA are, a special run was made. The data used were from channel 3 (RAW). The Red, Green and Blue groups were each split into two groups, and the classification functions produced by the program based on the first half of the data were used to classify the second half. The classification matrices at steps 1, 5, and 10 turned out to be as follows: (Table 5)

We see that the classification functions produced by the program do a good job of discrimination (86% vs. 93% overall) on color evoked responses. This gives encouragement to our intentions of using the classification functions ON-LINE in operant conditioning experiments.

PAIR WISE COMPARISONS TABLE # 4

*** Indicates 90% or over

RUN #	DATA DESCRIPTION	GROUPS/# CASES	CORRECT CLASSIFICATION PERCENTAGE ACHIEVED	# STEPS	VARIABLES CHOSEN (AFTER 10 STEPS)
	Red vs Blue				
15	Channel 1 Ortho	Red/48 vs Blue/49	***	2	22, 49, 5, 29, 27, 14, 8, 9, 12, 10
16	Channel 3 Raw	Red/48 vs Blu/47	***	3	29, 33, 26, 22, 79, 24, 21, 17, 20, 16
	Red vs Green				
17	Channel 1 Ortho	Red/48 vs Grn/48	***	2	20, 43, 10, 62, 29, 34, 26, 5, 12, 7
18	Channel 3 Raw	Red/48 vs Grn/48	***	2	33, 40, 10, 46, 29, 41, 21, 73, 64, 36
	Green vs Blue				
19	Channel 1 Ortho	Grn/48 vs Blu/49	***	7	27, 17, 9, 13, 11, 32, 4, 38, 56, 80
20	Channel 3 Raw	Grn/48 vs Blu/47	***	2	41, 34, 45, 10, 37, 64, 73, 80, 58, 18

	Red	Green	Blue	Red	Green	Blue	Red	Green	Blue
Red 1	10	3	11	21	0	3	24	0	0
Green 1	4	19	1	1	23	0	0	24	0
Blue 1	7	2	15	1	0	23	0	0	24
Red 2	10	1	13	11	1	12	18	0	6
Green 2	9	14	1	0	23	1	0	24	0
Blue 2	10	2	11	4	0	19	4	0	19
	STEP 1			STEP 5			STEP 10		

TABLE 5

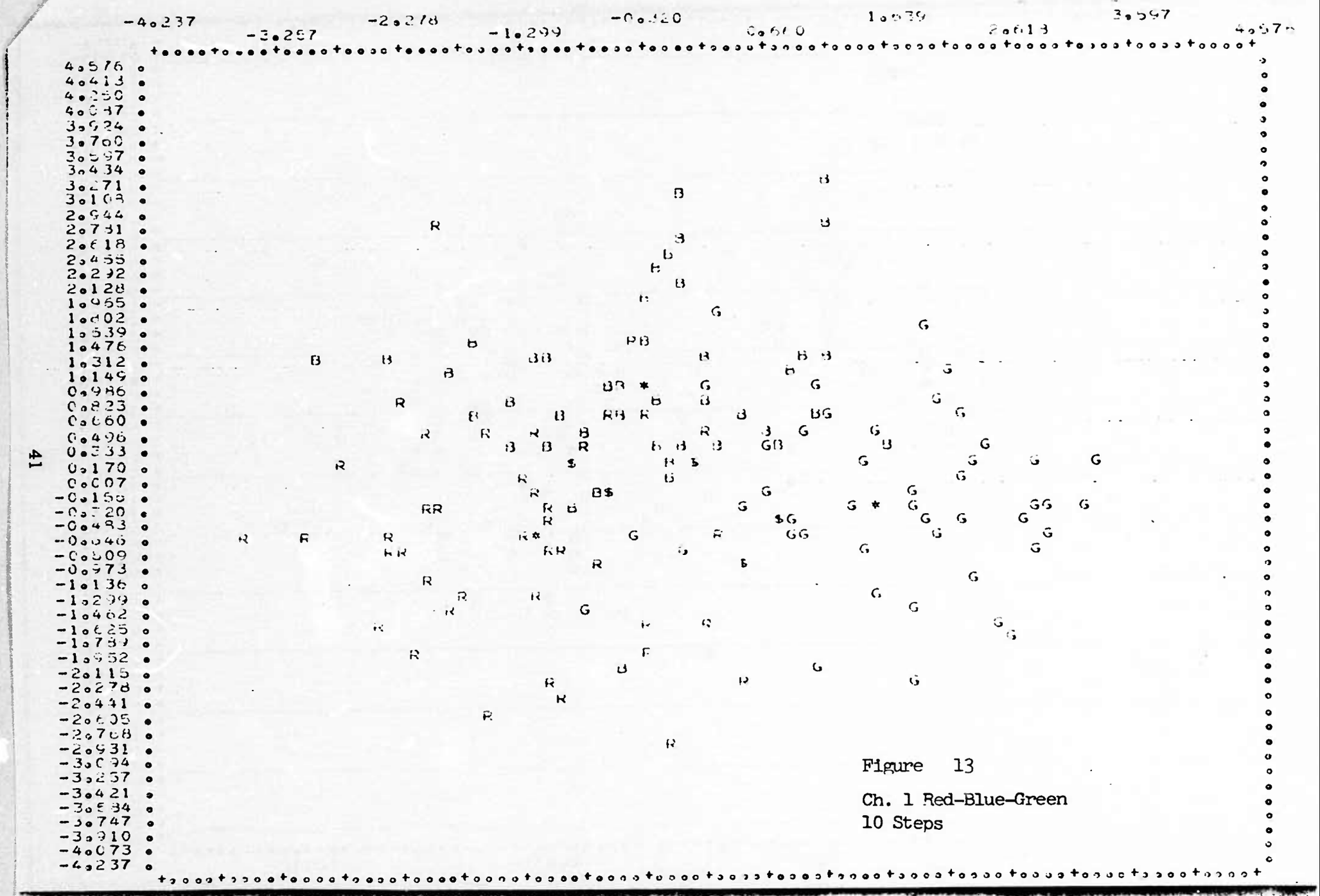
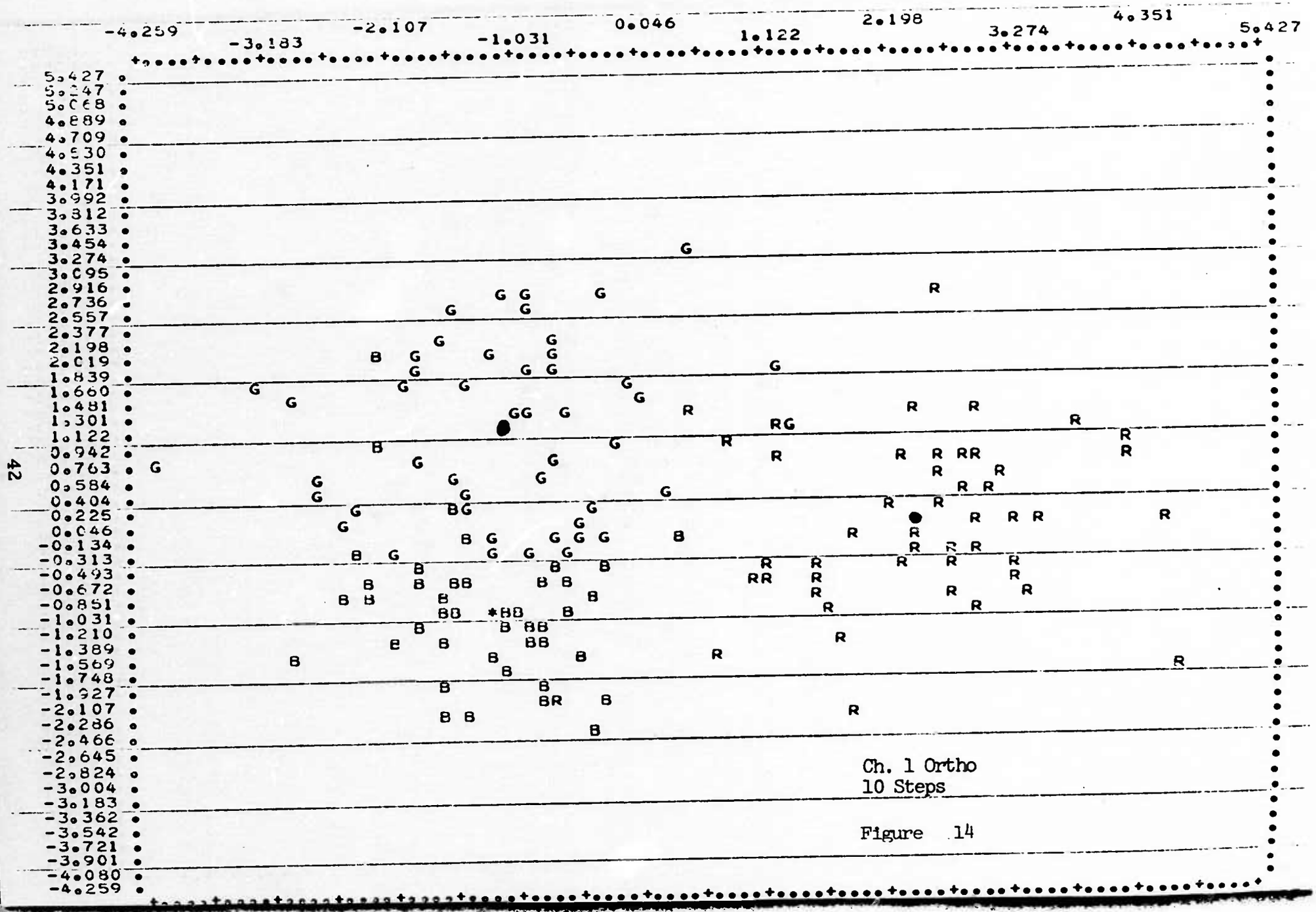


Figure 13

Ch. 1 Red-Blue-Green
10 Steps



Ch. 1 Ortho
10 Steps

Figure 14

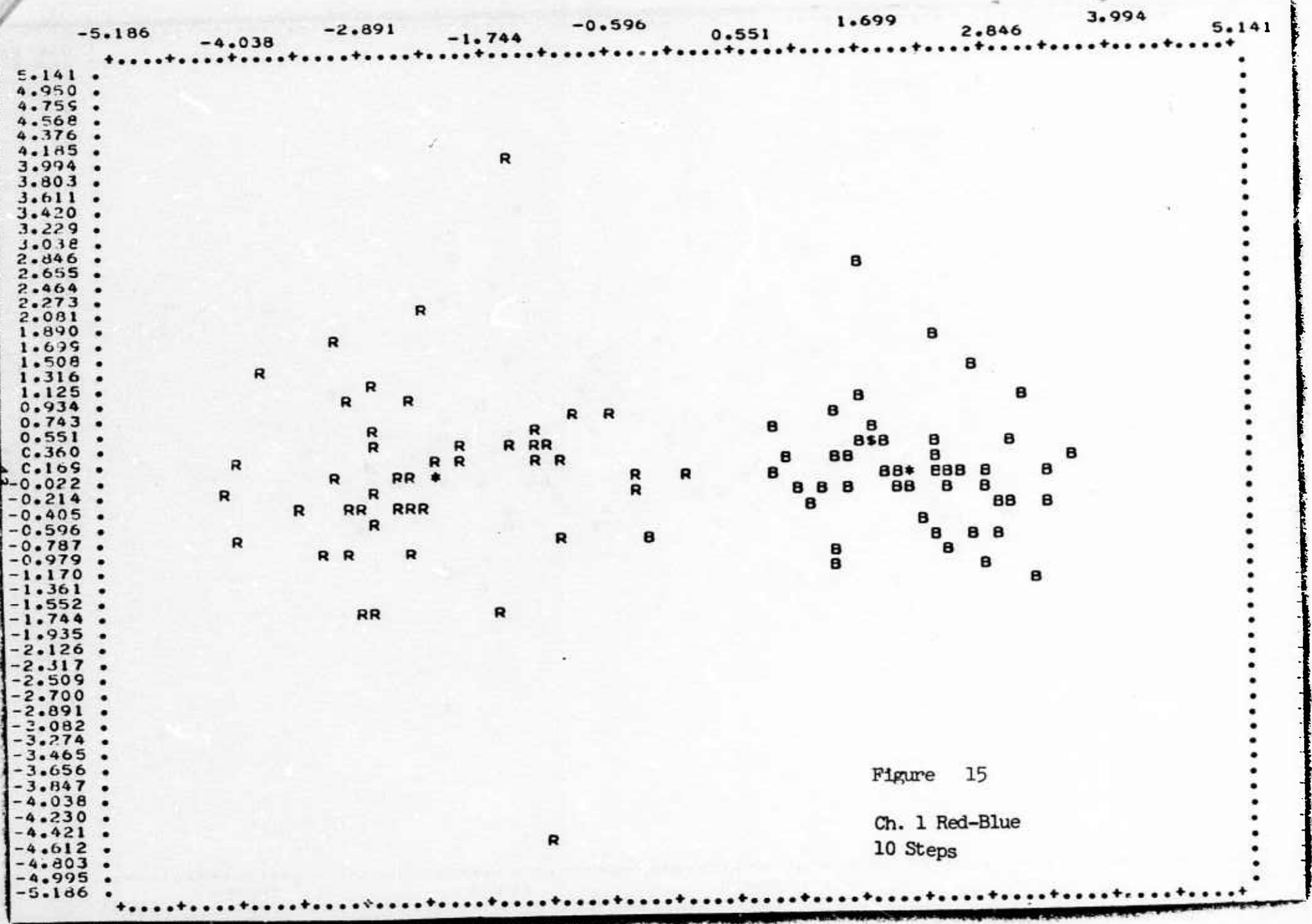
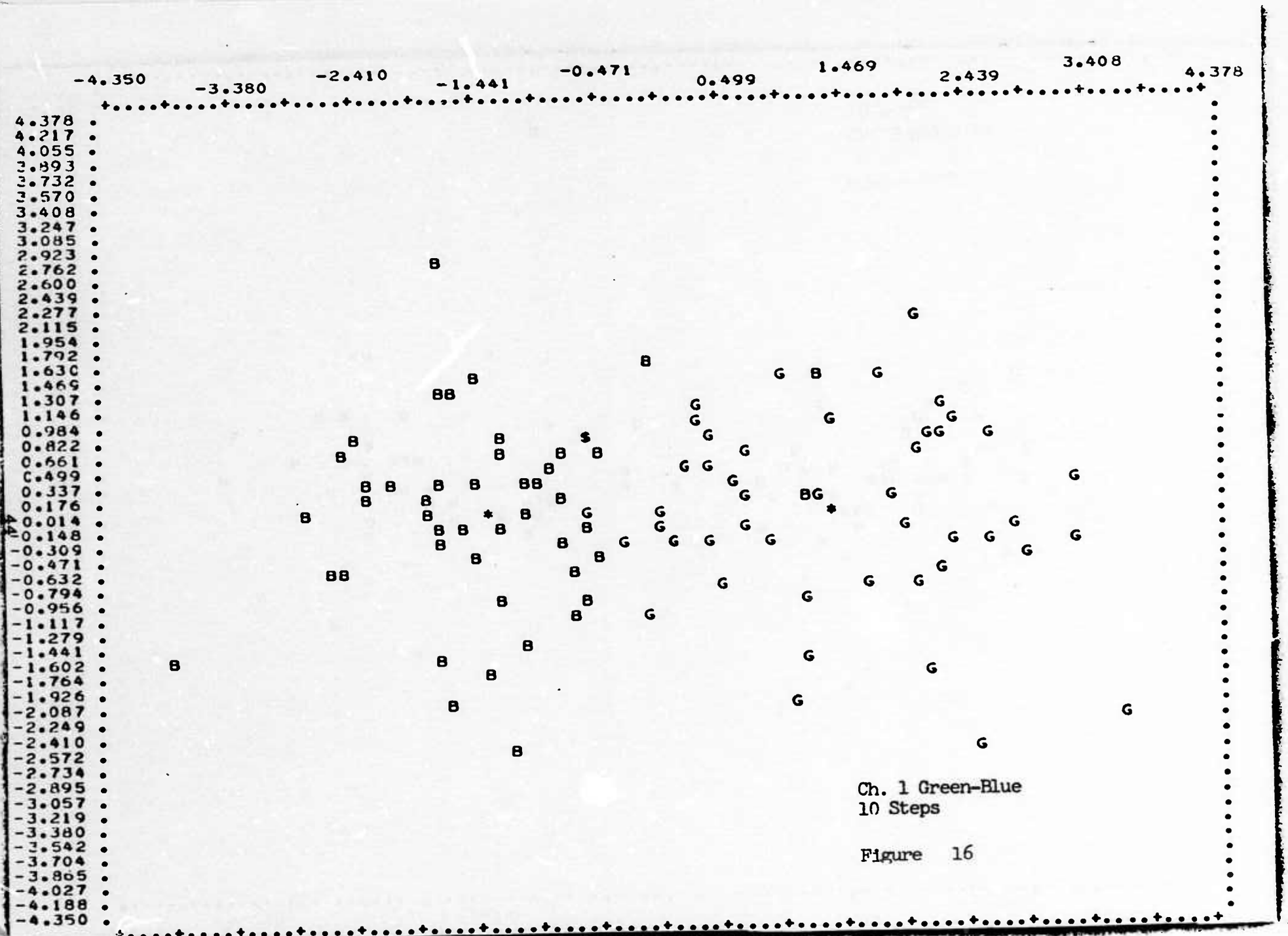


Figure 15

Ch. 1 Red-Blue
10 Steps



Ch. 1 Green-Blue
10 Steps

Figure 16

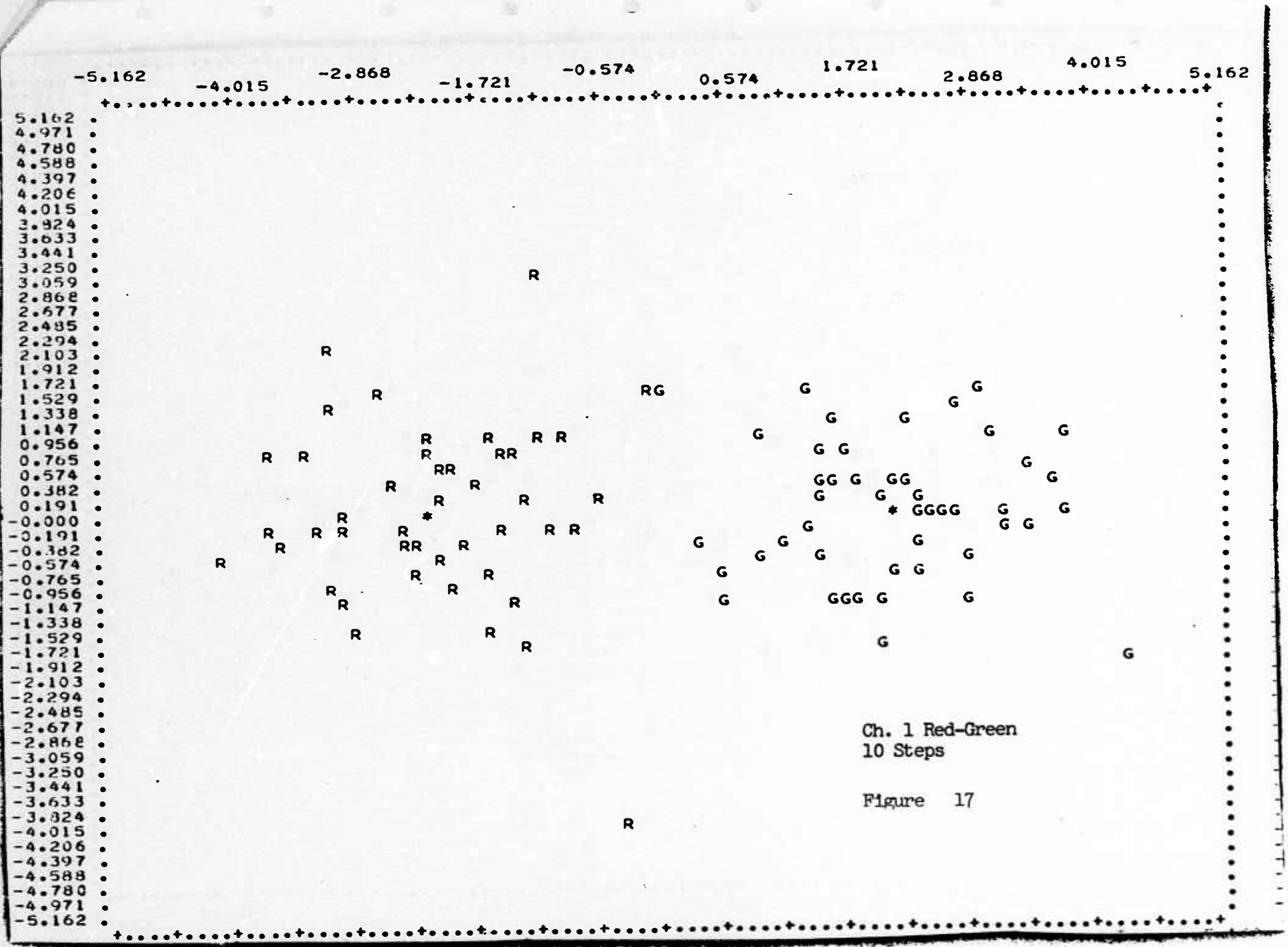
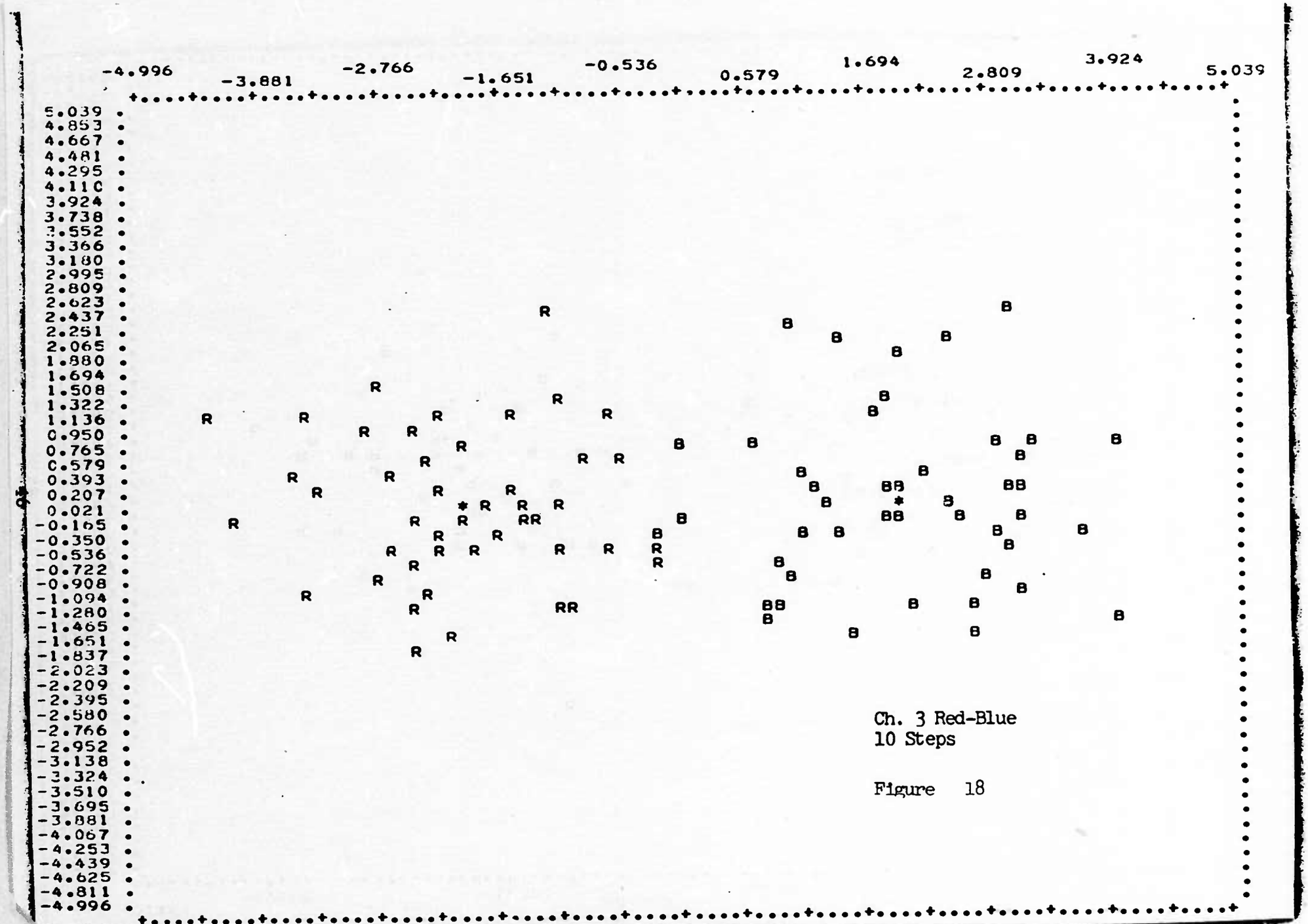
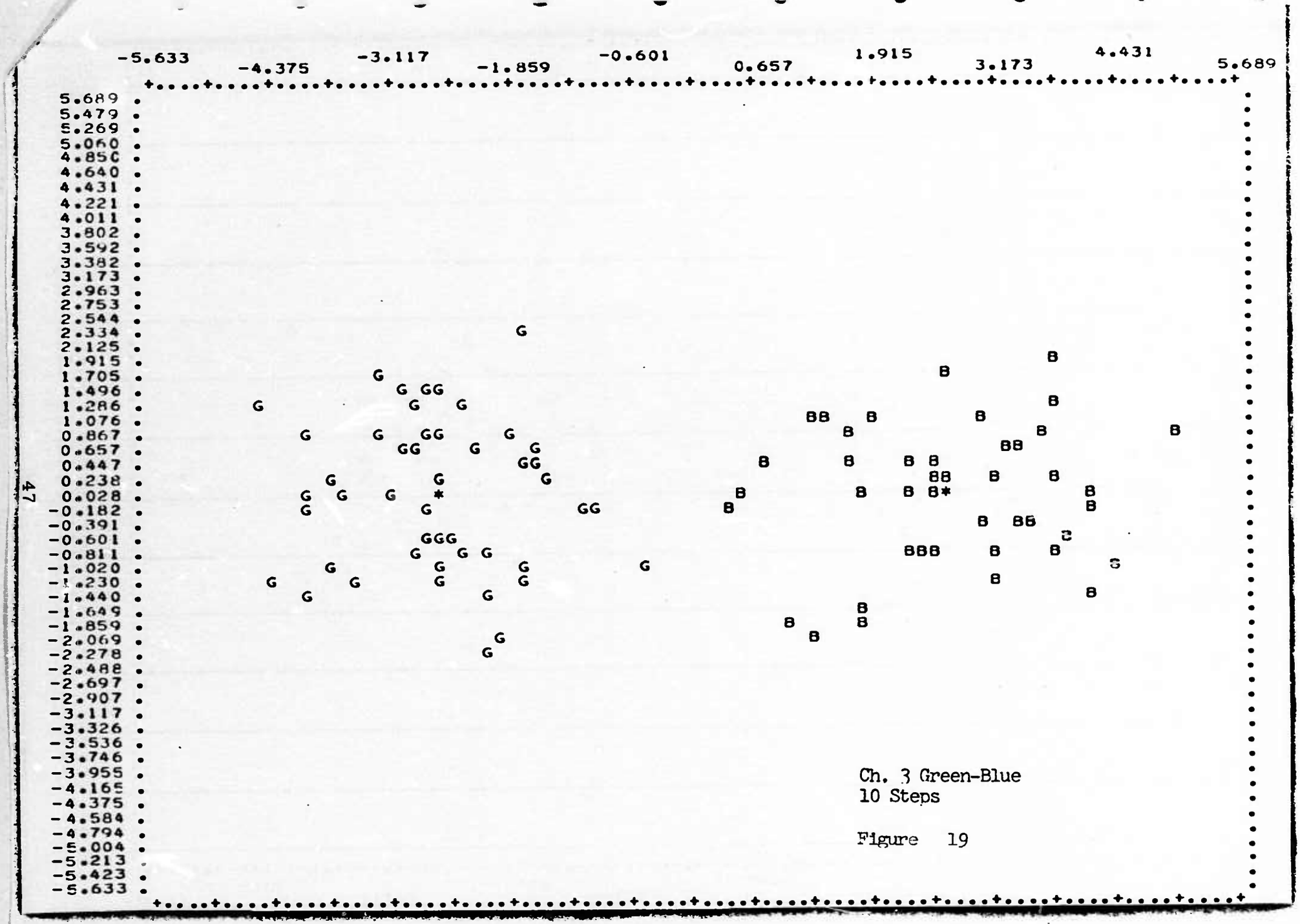

-5.162
-4.015
-2.868
-1.721
-0.574
0.574
1.721
2.868
4.015
5.162
Ch. 1 Red-Green
10 Steps

Figure 17



Ch. 3 Red-Blue
10 Steps

Figure 18



Ch. 3 Green-Blue
10 Steps

Figure 19

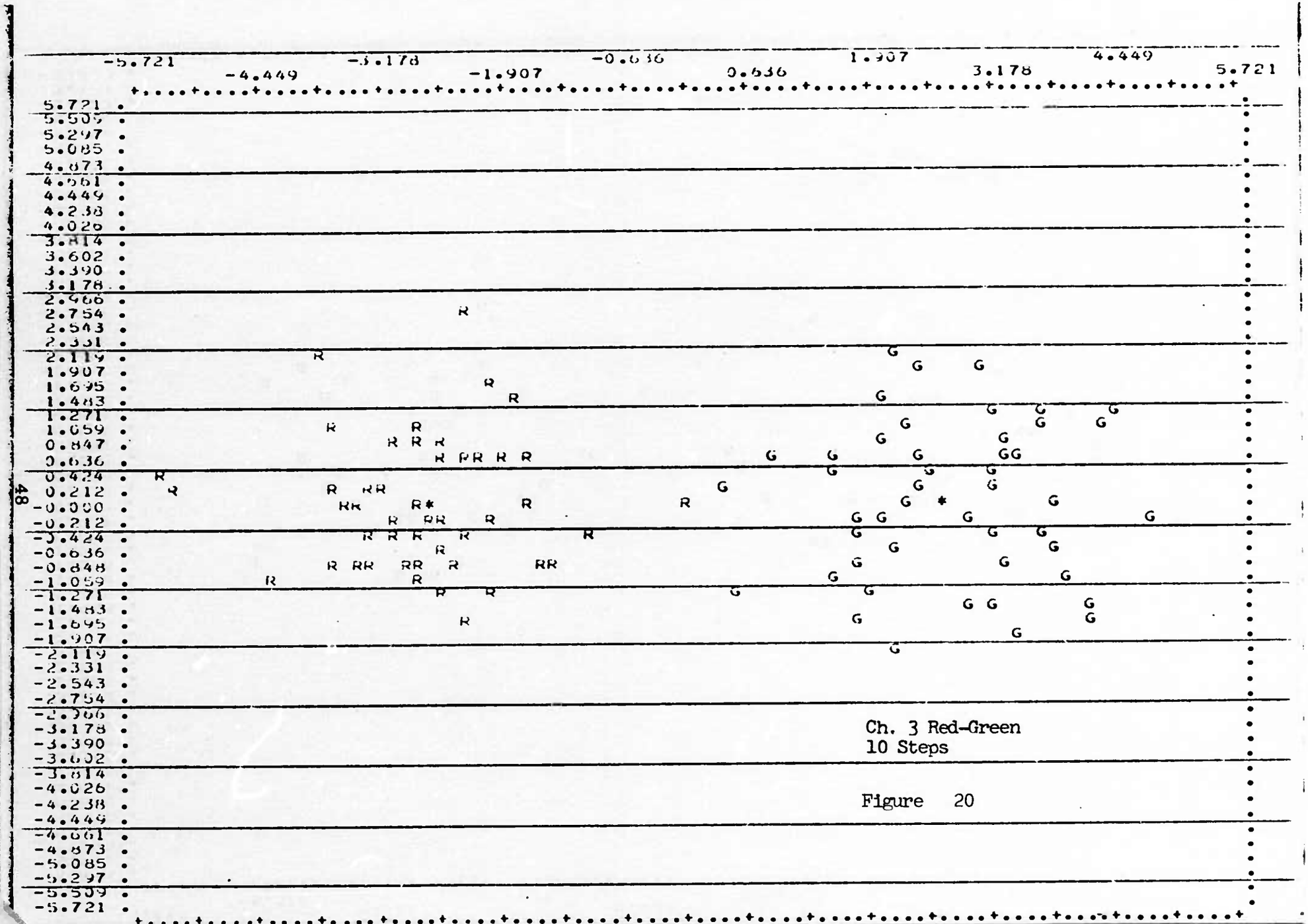

-5.721
-4.449
-3.178
-1.907
-0.636
0.636
1.907
3.178
4.449
5.721
Ch. 3 Red-Green
10 Steps

Figure 20

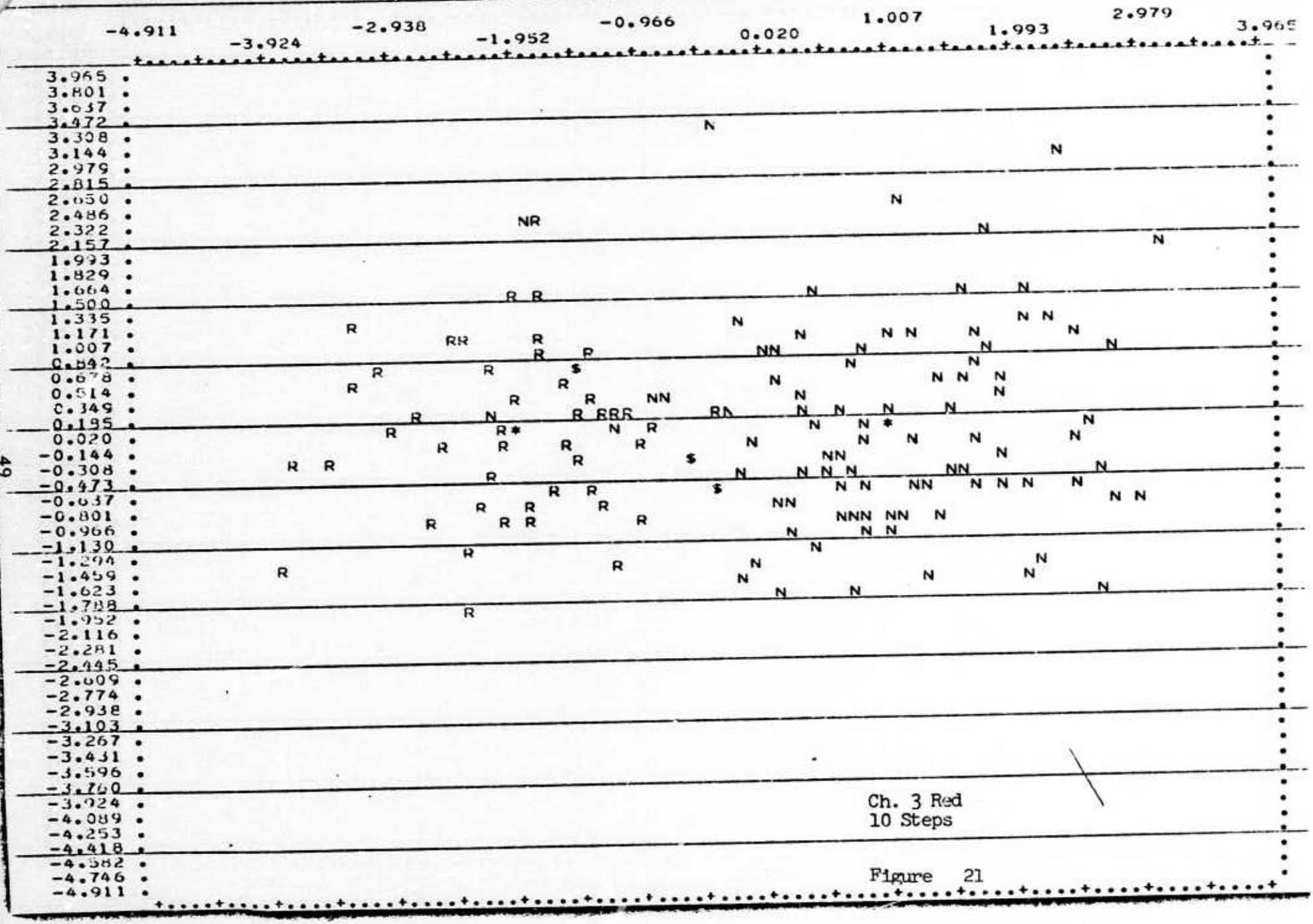
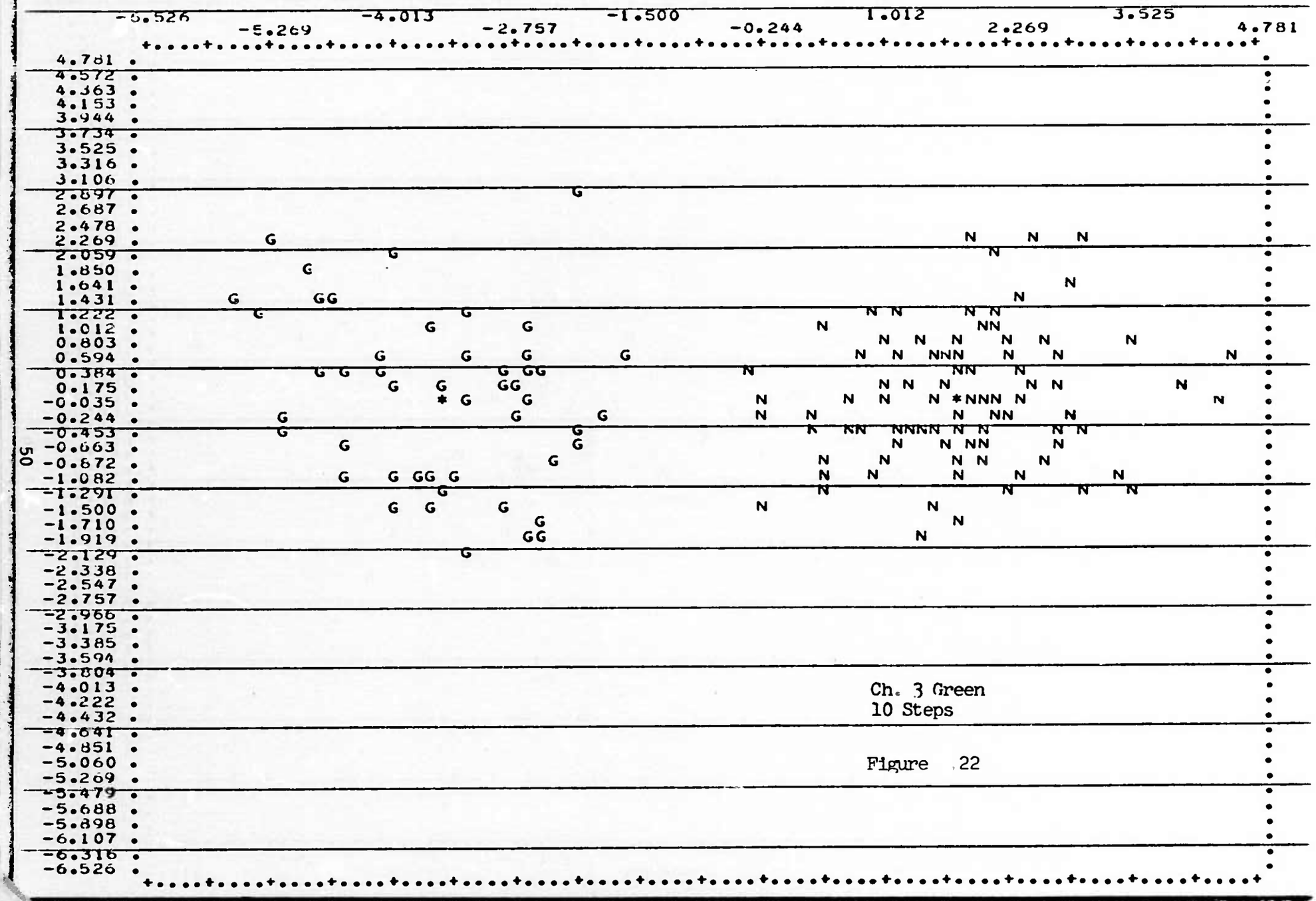

-4.911
-3.924
-2.938
-1.952
-0.966
0.020
1.007
1.993
2.979
3.965
Ch. 3 Red
10 Steps

Figure 21



Ch. 3 Green
10 Steps

Figure 22

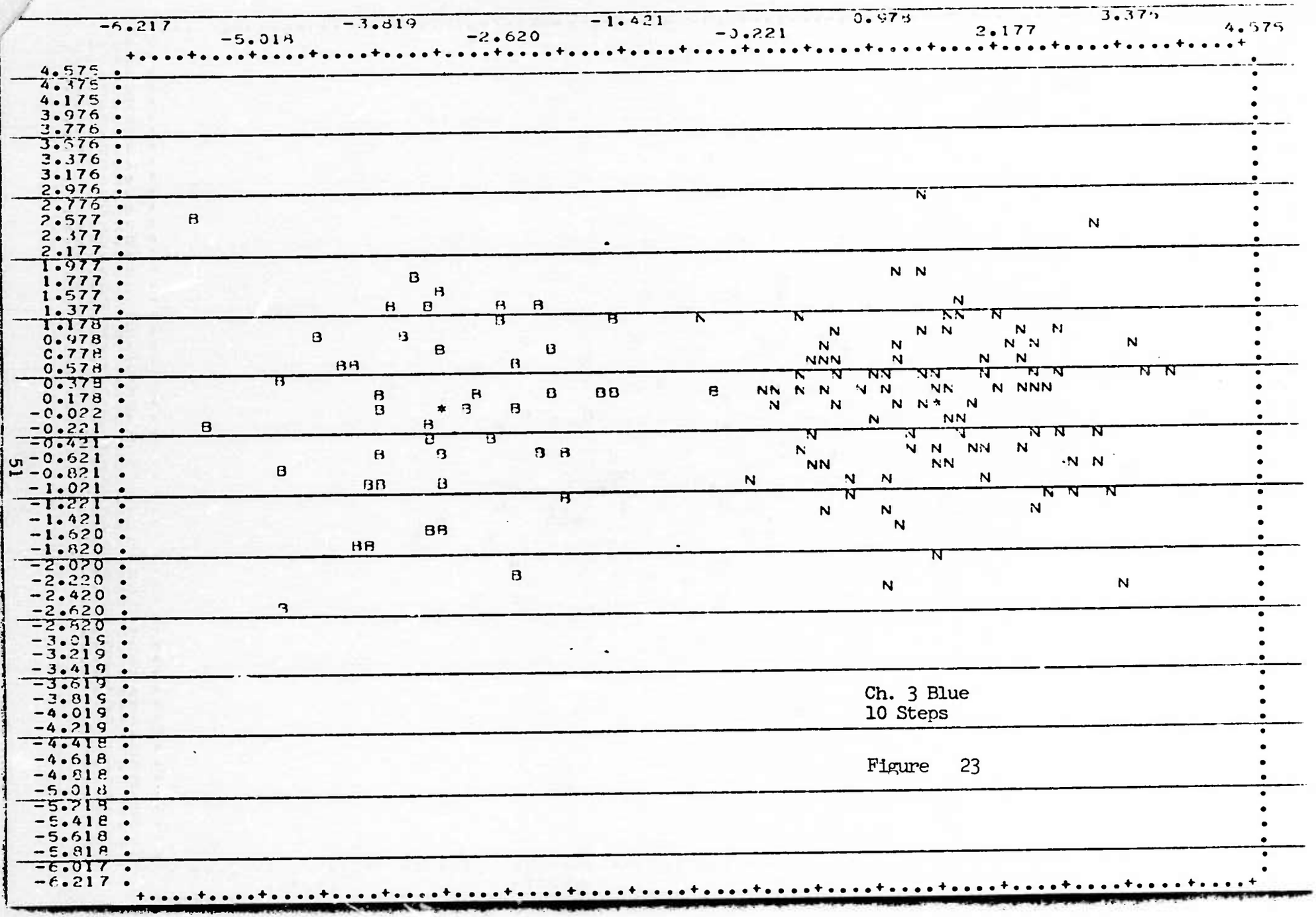

-6.217
-5.018
-3.819
-2.620
-1.421
-0.221
0.978
2.177
3.375
4.575
Ch. 3 Blue
10 Steps

Figure 23

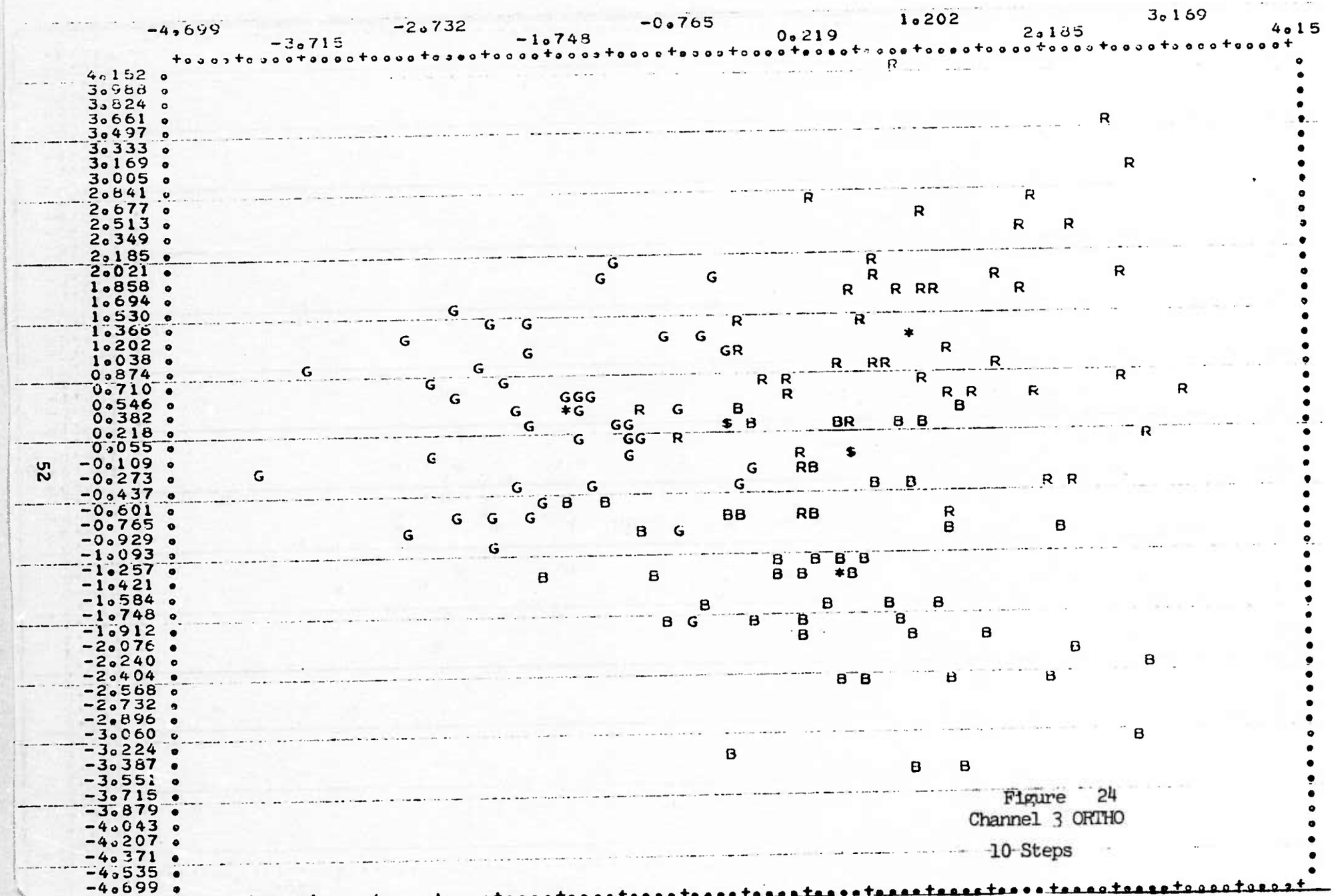
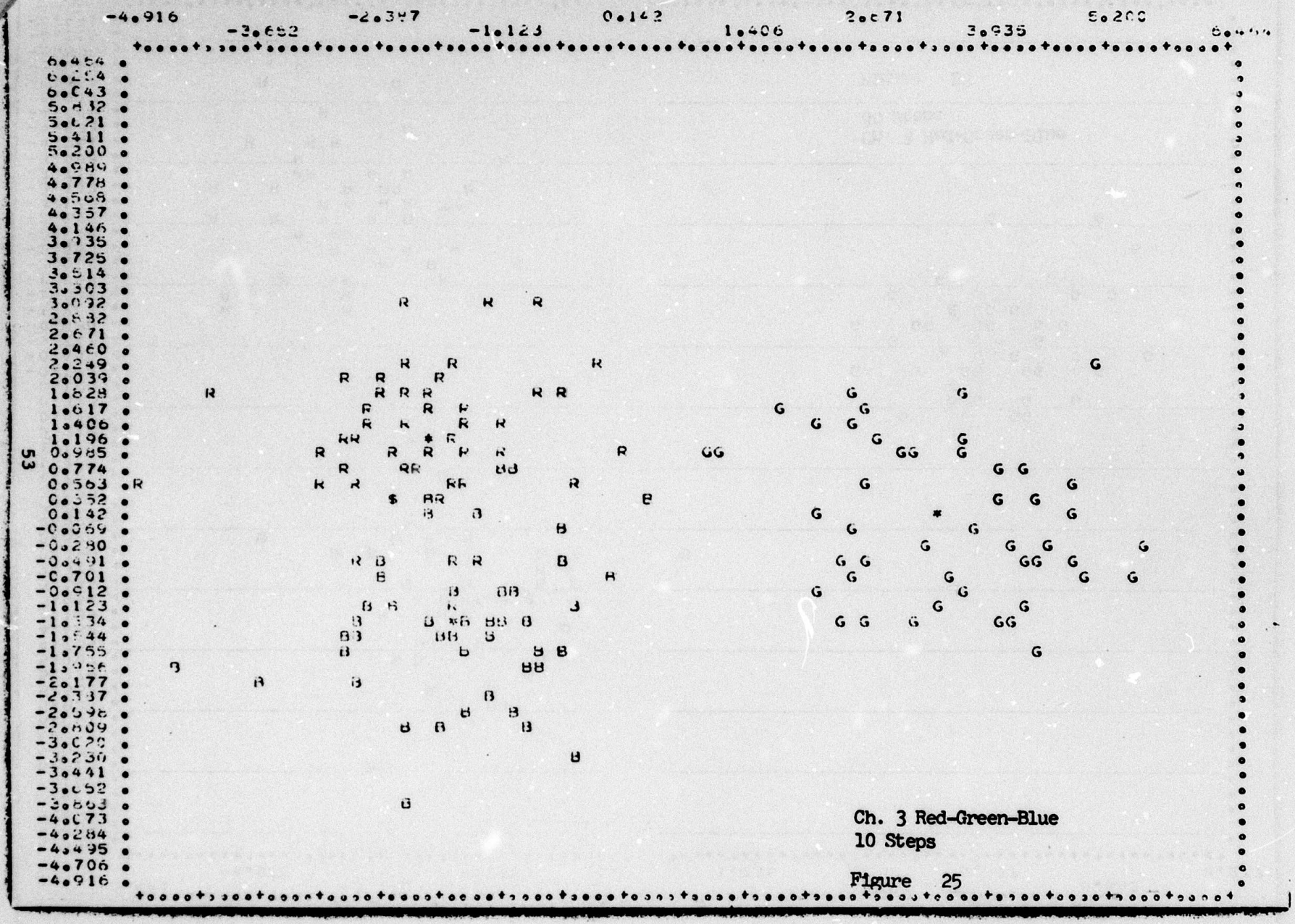
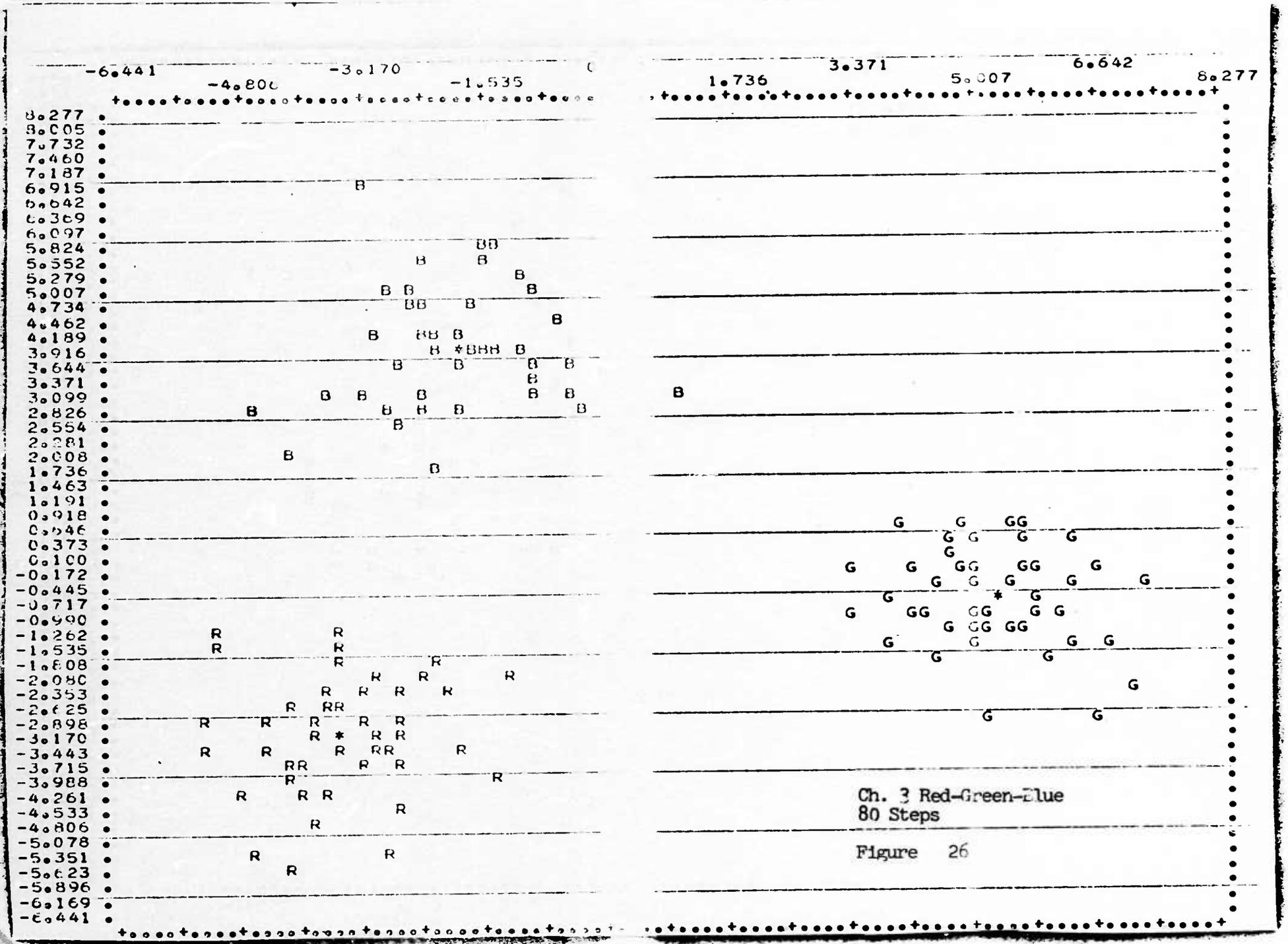


Figure 24
Channel 3 ORTHO
10 Steps



Ch. 3 Red-Green-Blue
10 Steps

Figure 25



Ch. 3 Red-Green-Blue
80 Steps

Figure 26

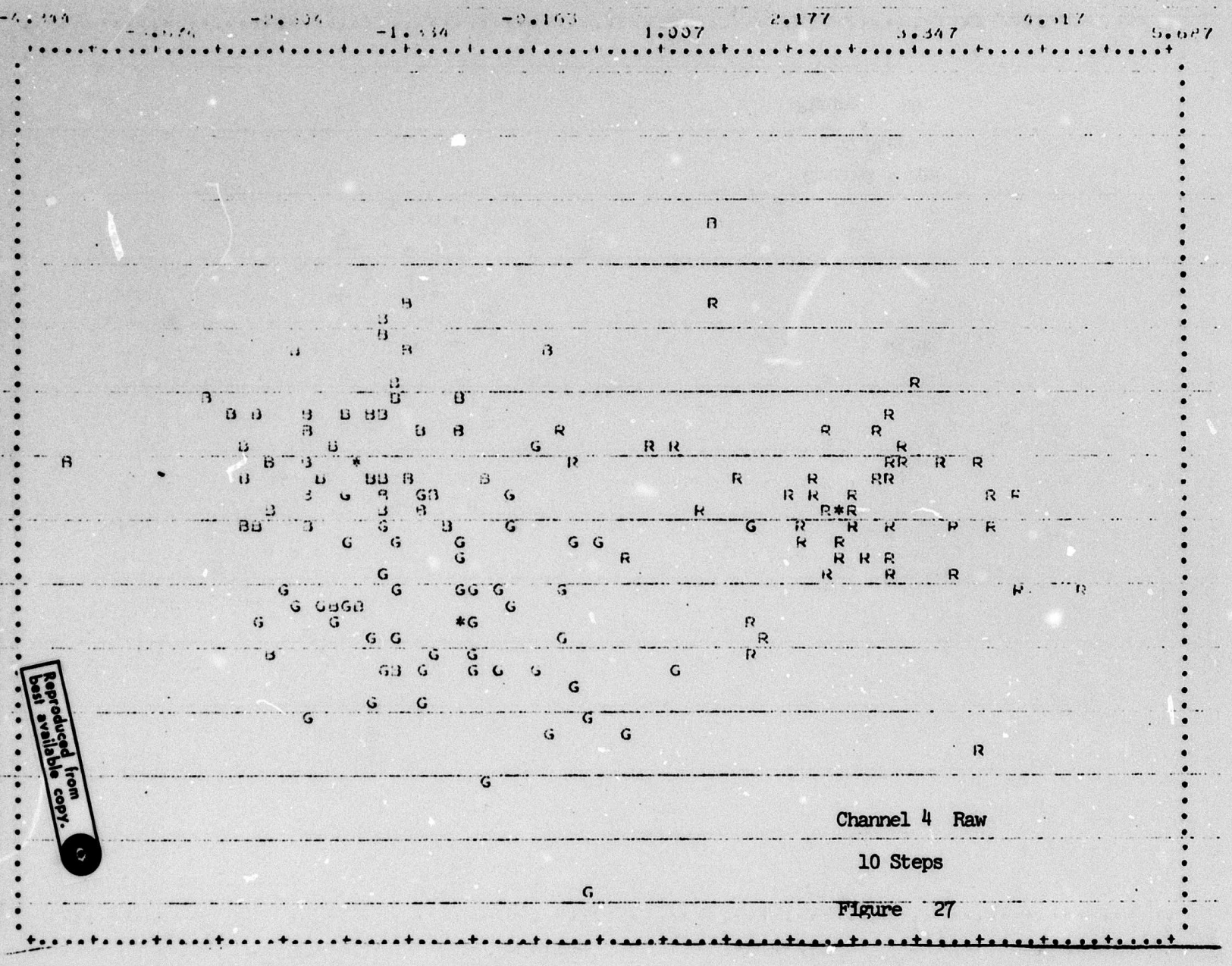


Figure 27

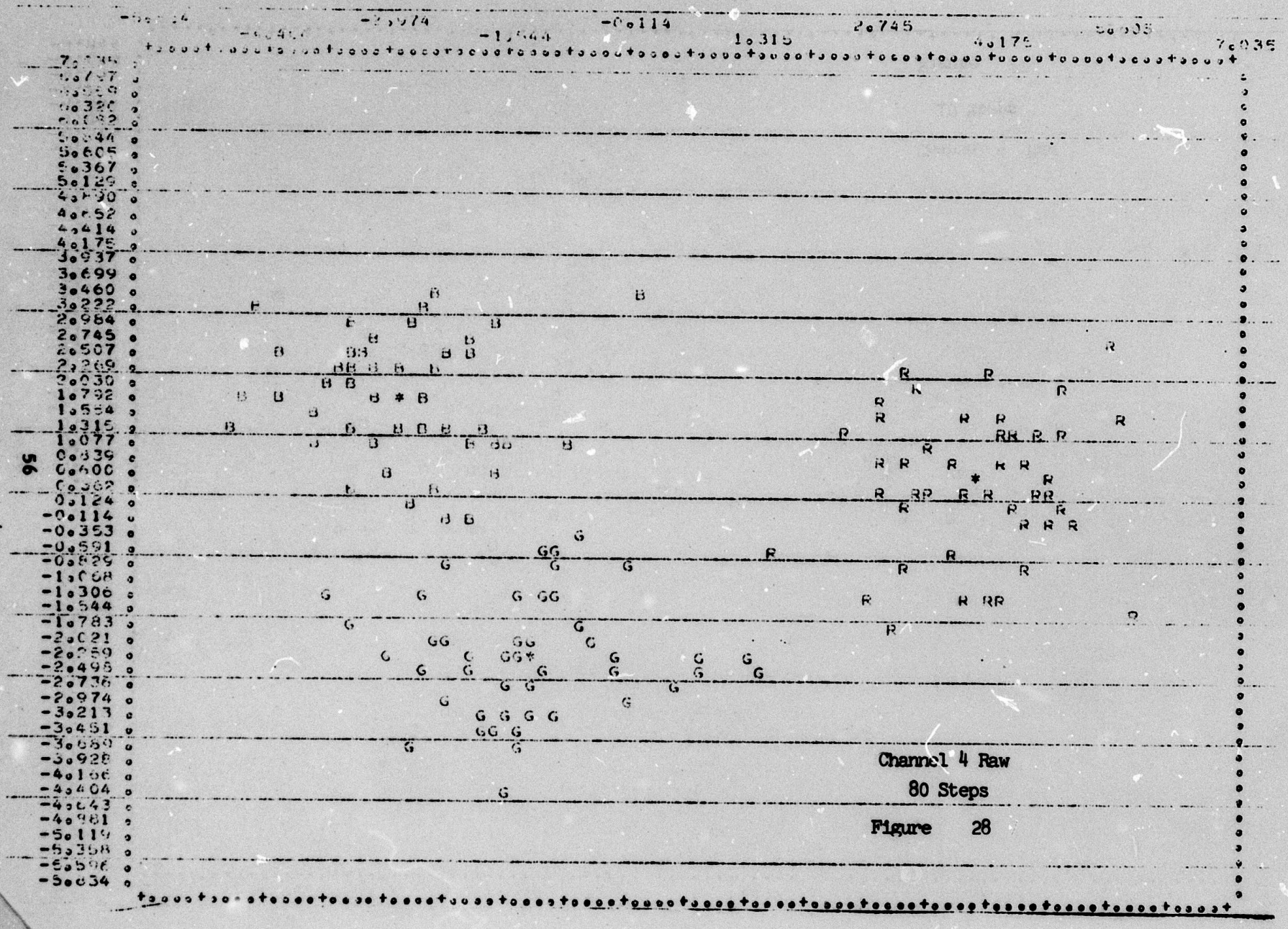


Figure 28

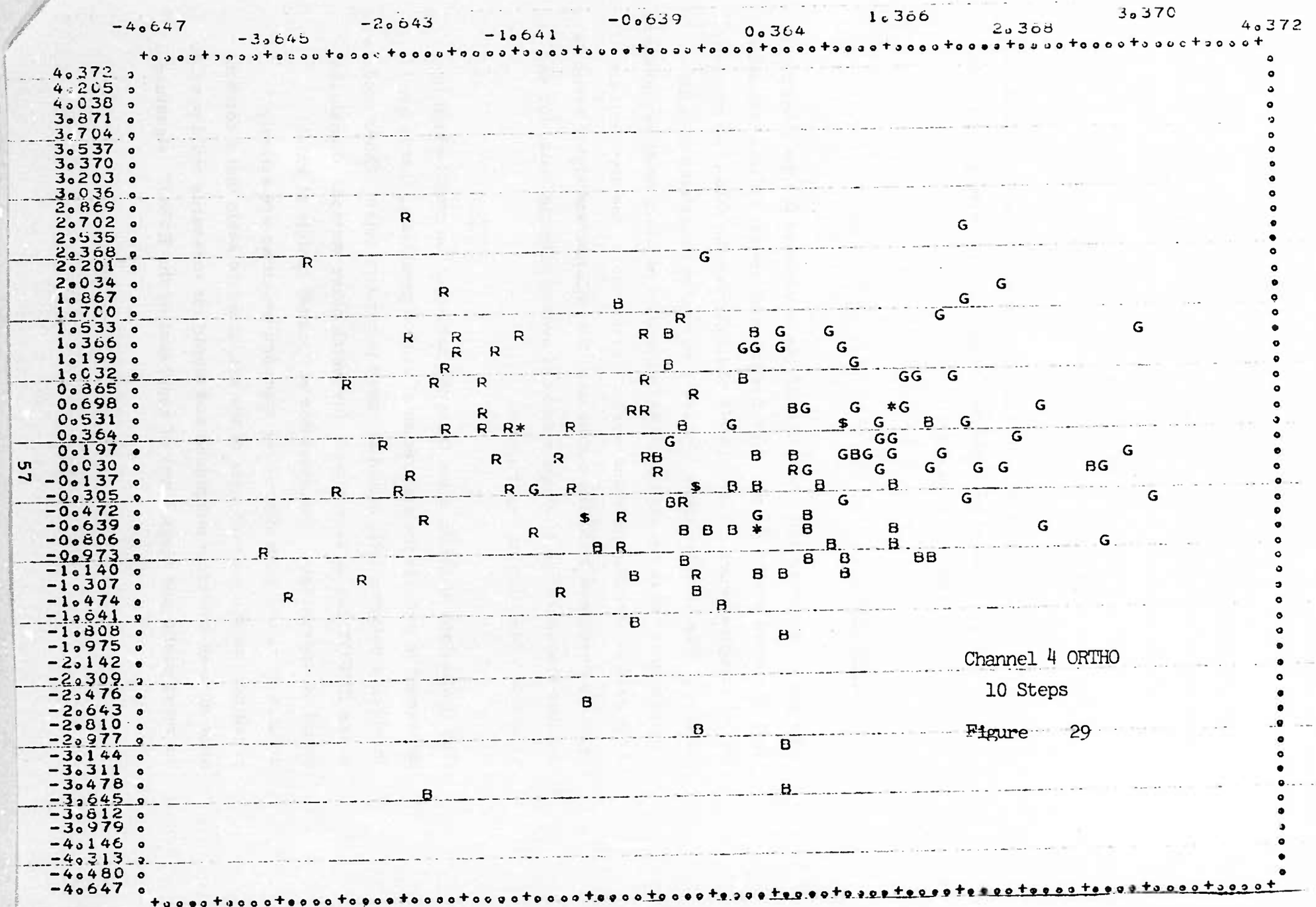

-4.647
-3.645
-2.643
-1.641
-0.639
0.364
1.366
2.368
3.370
4.372
Channel 4 ORTHO
10 Steps

Figure 29

A pictorial display of the classification and separation ability of SWDA is provided in the form of the now classic canonical separation map. Each epoch is located in the two-dimensional space and labeled with the first letter of its group name. An asterisk is placed at the center of "mass" of each group, and overlaps are indicated by a $.

Figures 13 and 29 are representative canonical maps which allow further comparisons of the effect of channel, color, orthogonalization and number of steps on the separation.

CONCLUSIONS

The use of stepwise discriminant analysis is valuable for the classification of evoked potential data. The program efficiently selects that subset of samples which can accurately characterize the data in an optimum manner. The samples which are selected can be associated with the "components" of the evoked potential waveform to which most researchers have paid attention in previous work. Furthermore, the discriminant function developed by SWDA can be used for efficient and highly accurate on-line classification of single epochs of evoked potential data, for use in operant conditioning experiments.

The limitations of SWDA arise from the nature of the model which is presumed to underly the generation of evoked potentials, that is one in which a deterministic signal is added to random noise. Other models of the EVPOT can be entertained, for which other methods of analysis would be appropriate. The detection of "peaks" (points at which $dv/dt = 0$) is one such alternative approach which we are actively pursuing. At the present state of the art, it would seem that a combination of peak detection techniques and amplitude measures could provide the most useful and elegant way of representing the EVPOT "signature".

Work is continuing on a rewriting of SWDA into 360/91 assembly language to make it a highly interactive subtask of our monitor system. A further step would be to modify the BCI monitor software so that it can be accessed and controlled by a remote ASCII terminal connected to a standard telephone line operating under TSO (Time Shared Option).

REFERENCES

Brown, P.K., and Wald, G. "Visual pigments in single rods and cones of the human retina", Science, 1964, 144; 45-52.

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Marks, W.B., Dobelle, W.H., and MacNichel, E.F., Jr. "Visual pigments of single primate cones". Science, 1964, 143; 1181-1182.

release date 120173
VIC

BCI EEG DATA FORMAT

General Comments:

Following is a tentative description of the format and layout of the EEG epoch-oriented data for all processing transactions involving the BRAIN COMPUTER INTERFACE (BCI) lab. All current and future BCI applications or systems programs will follow this format or an update version thereof. Also, all data from external sources must be pre-converted if use of any part of th BCI system is intended. Note that the format described below is compatible with standard IBM/360 word and byte sizes, which can be read or written by any high level language such as FORTRAN IV or PL/1, or even by machine dependent languages such as the as 360 Assembler Language. Thus the format is intended to be ultimately compatible with any application on 360/370 systems.

General Data Format:

BCI EEG data is grouped into logical and physical units called 'epochs'. Each epoch corresponds to data collected during a discrete time period, while a specific task is being performed by the subject, or while the subject is being exposed to a given set of environmental conditions. For example, an epoch might consist of 8 channels of EEG data collected during a 1/2 second interval following red strobe flash. over a green background. There are usually many such epochs per experiment, and groups of epochs often have some common characteristic. They are grouped together into 'epoch strings', with n epochs in each string, (numbered 0 through n-1.) Each epoch is broken down into two parts:

(1) the epoch header
(2) the epoch data.

The epoch header consists of useful and necessary information about the epoch, such as the subject's identification code, the task performed, the length of the epoch, how many channels of data are present, the sampling rate of the collection, and so on.
The epoch data follows directly, containing the actual experimental data for that particular epoch.
The logical length for the 'records' that compose each epoch may vary, depending on the data, from 40 to 80 bytes. 40 bytes is the minimum due to the size and form of the epoch header (see below). 80 bytes was chosen as the maximum because it is standard card image size, and because it appears most unlikely that more than 80 bytes will ever be needed (see below).

Epoch Format:

(1) Epoch Header

The epoch header (tentatively) is composed of 11 records. Each record contains information about the epoch data to follow. Because it contains the type of information presumably required with most existing or future BCI applications software, it was decided that the header should be a modified version of the input control cards to the UCLA Biomed program BMDX92 (auto- and cross-spectral analysis). These records are in 360 character mode, and as mentioned are no less than 40 characters in length. (Only 40 characters are used. If the logical length of the epochs is greater than 40, then the header records are padded to the right with blanks, as usual). Thus all unspecified columns below are blank.

Card 1:

col 1-6:	'PROBLM'
col 7-12:	6 byte run identification field
col 13-16:	number of samples (FORTRAN 'I4' fixed point)
col 17-18:	number of channels (FORTRAN 'I2' format)
col 19-21:	number of frequency bands resolved ('I3')
col 22-25:	sampling rate ('I4')
col 26-40:	(reserved - blank - X92 compatible)

Card 2:

col 1-6:	'PREFLT'
col 7-40:	(reserved - blank - X92 compatible)

Card 3:

col 1-6:	'TITLES'
col 8-12:	'EPOC:'
col 14-16:	epoch no. (location in string ('I3')
col 19-23:	'EXPR:'
col 25-27:	epoch string identification ('A3'), task id
col 30-34:	'SUBJ:'
col 36-38:	subject id - initials ('A3')

Card 4:

col 1-6:	'TITLES'
col 8-12:	'DATE:'
col 13-16:	date of experiment/epoch - mmdd ('2I2')
col 19-23:	'STMT:'
col 24-27:	stimulus type (0-7) for this epoch ('I4')
col 30-34:	'EPXS:'
col 35-38:	number of epochs in each string ('I4')

Card 5:

col 1-6:	'TITLES'
col 8-12:	'NSMP:'
col 13-16:	number of samples in the epoch

col 19-23: 'NSED:'
col 24-27: number of samples in epoch delay ('I4')
(used for artifact detection prior to epoch data)
col 30-34: 'NSWD:'
col 35-38: number of samples between warning stimulus
and main stimulus (if applicable) ('I4')

Card 6:
col 1-6: 'TITLES'
col 8-12: 'SINT:'
col 13-16: scan interval (millisec) or 1/rate ('I4')
col 19-23: 'NACH:'
col 24-27: the number of channels
col 30-34: 'DCRL:'
col 35-38: decision rule used for grouping of
similar stimuli ('I4')

Card 7:
col 1-6: 'TITLES'
col 8-12: 'ARPD:'
col 13-16: artifact detection threshold (levels/2048) ('I4')
col 19-23: 'ERPD:'
col 24-27: evoked response peak detection threshold ('I4')
(levels/2048 for peak detection)
col 30-34: 'NSTM:'
col 35-38: number of stimulus types ('I4')

Card 8:
col 1-6: 'TITLES'
col 8-12: 'SEED:'
col 13-16: seed for any applications random number
generator (zero if not applicable) ('I4')
col 19-23: 'GRPS:'
col 24-27: no. groups (input), chosen grp (output) ('I4')
col 30-34: 'CLOK:'
col 35-38: time the epoch was taken (hhmmss - '3I2')
may be zero if not needed

Card 9:
col 1-6: 'TITLES'
col 8-12: 'EKGR:'
col 13-16: EKG rate ('I4')
col 17-40: reserved for future use

Card 10:
col 1-6: 'TITLES'
col 8-12: 'BASL:'
col 13-16: baseline level ('I4')
col 17-40: reserved for future use

Card 11:
col 1-6: 'TITLES'
col 8-12: 'CNVA:'
col 13-16: contingent negative variation amplitude ('I4')

col 17-40: reserved for future use

Card 12:
col 1-6: 'TITLES'
col 8-12: 'RACT:'
col 13-16: reaction time ('I4')
col 17-40: reserved for future use

Card 13:
col 1-38: 'NAMCHN C01 C02 C03 C04 C05 C06 C07 C08'

Card 14:
col 1-38: 'NAMCHN C09 C10 C11 C12 C13 C14 C15 C16'

Card 15:
Fortran type variable format card which can be used to read the data to follow, of the form '(mmAnn)' or '(mmFnn.pp)', where 'mm' is actually the number of channels, 'nn' the width of each value field, and 'pp' the number of decimal digits assumed (if any).

All fields (except 'channels', 'sampling rate', 'number of samples', 'EPXS', 'EPX', 'EXPR', 'NSMP', and 'NACH') may be left blank or zero if the field meaning is not applicable to the specific data base structure. The exceptions above, however, must contain valid data.

(2) Epoch Data

From the above description of the variable format it can be seen that each record contains one and only one scan. Each scan (record) contains one EEG voltage value for all of the channels. Thus, if there are 8 channels involved, and 200 samples per epoch, there would be the usual 15 epoch header records, and 200 epoch data records, each of which contains 8 values (eg: 8F5.0).

A sample epoch follows:

```
PROBLMEXAMPL0200 8 64 128
PREFLT
TITLES EPOC: 002  EXPR: 2TR  SUBJ: FLC
TITLES DATE:0409  STRT:1438  EPXS:0007
TITLES NSMP:0200  NSED:0100  NSWD:0100
TITLES SINT:0008  NACH:0008  DERL:0000
TITLES ARPD:0600  ERPD:0050  NSTM:0002
TITLES SEED:0000  GRPS:0000  CLOK:162221
TITLES EKGR:0409
TITLES BASL:0200
TITLES CNVA:0008
TITLES RACT:0600
NAMCHN C01 C02 C03 C04 C05 C06 C07 C08
NAMCHN C09 C10 C11 C12 C13 C14 C15 C16
(8F5.0)
+0106+0142-0118+0095-0057-0087-0038-0082
+0122+0159-0050+0138-0138-0178-0125-0083
+0221+0099-0130+0078+0100-0122-0229-0003
                      .
                      .
                      .
+0104+0207+0017+0012-0048-0081-0225-0019
```

COMMENTS

This epoch is therfore 15+0200=0215 records long. There are 0200 samples in each epoch for each of the 8 channels of data; the sampling rate is 128 samples/second. This particular epoch is epoch number 002 of a 7-epoch string called '2TR' for subject 'FLC'. The epoch was taken on April 9 at 4:22:21. The data following the header is structured into 0200 records containing 8 5-column values in FORTRAN 'F' floating point format. Each record forms one scan.

BCI/UCLA-BC

Release date 110173

THE BCI MONITOR SYSTEM

The BCI Monitor System runs as a job (task) in an OS/MVT environment on the IBM 360/91 at the Campus Computing Network located at UCLA. It serves as a powerful and general means of supporting and monitoring the BCI EEG data collection and analysis system. The system is in fact a computer network that involves 3 online computers for real-time control and analysis (the 360/91, an Imlac PDS 1, and an SDS 920), and on occasion several offline computers including a local PDP-10 and several distant processing sites reached through the ARPA Network, all used for pre- or post-experimental computation. The three online computers are connected by a hardware data link over which control and/or experimental data may be transmitted. Both real-time and offline applications programs on the receiving computer (usually the 360/91 or the Imlac) do the 'number crunching' and various statistical analyses of the incoming data. Plots, maps, data for visual feedback and stimuli, tables, and so on may be produced either immediately during the experiment or later. The generated data may be sent back over the same link if desired.

With this in mind, the Monitor system was designed to serve the following functions:

(1) To serve as an interactive console system supporting

several operational stations on a time-shared basis. A user of the Monitor obtains access to the system via a CRT-keyboard apparatus similar to Techtronic or Computek units (CCI's). (Note: a Monitor user may be the actual experimenter(s), applications programmers running data analyses, systems programmers supervising the link, etc.) He communicates with the system via smaller and specialized software subprocessors. Each subprocessor performs a specific task, yielding certain information on system status, user status, and so on (for example, one displays the current state of the Monitor's core memory, while another the status of the users currently signed on, another the status of all Monitor subtasks (see below), another the status of the IBM 360/91 under which the system runs. Each subprocessor may be accessed from any other subprocessor (the user may enter any of them to gather the information he needs). In general however, the commands in these subprocessors only effect a specialized section of the Monitor system, usually within the scope of the subprocessor involved. Control and supervision of the various system-wide functions and of the line handler (see below) is accomplished by the use of special commands which may be entered at any time from any subprocessor. These 'system commands' generally do not obtain information but initiate a specified system operation (such as subtask control, as described below).

(2) To initiate the line handler subtask which performs the actual input/output operations on the data over the link. This task operates as a subsidiary task of the Monitor task,

running independently and asynchronously, but still under complete supervision and control of the Monitor. This is feasible on the 360/91 with its multitasking environment.

(3) To control the line handler subtask, allowing specification of different data paths, allowing different data path directions and destinations, and so on.

(4) To monitor the current status of the line handler subtask, thus obtaining information concerning what data is being currently transferred, where the data is being sent to or from, when the transfer is complete, whether it was successful, etc. It allows the Monitor user to keep tabs on the flow of data to and from the computers involved.

(5) To purge the line handler subtask when it has completed its work, or to cancel its operation for any reason (e.g. abnormal termination).

(6) With the line handler subtask in charge of controlling the flow of data, other subtasks can be run under the Monitor system. These other subtasks may run concurrently with the line handler or separately (still 'subtasks' of the Monitor task in the context described above), and would be under the same initiation, control, and termination procedures as described previously for the line handler. In general, these other subtasks would be applications and data management programs, and might include various statistical explorations such as multi-dimensional tree analysis, non-linear mapping, analysis of variance with transgenerations, spectral analysis, stepwise discriminant analysis, and so on. Thus, they would not actual

take care of the link I/O operations themselves as does the line handler subtask, but would rather utilize the data flow of the link to perform the actual analysis of the information (immediately as it is transmitted through the link, or offline any time after the experiment upon data files saved on permanent storage devices). For example, such subtasks would, in real time, take data from the line handler, process it, and use the line handler to pass back the processed results, with all subtasks running concurrently with the experiment and with the console users time-sharing facilities.

These subtasks, then, can write or read data to or from any storage device available to the computer(s) involved, such as magnetic tape, disk, drum, cards, paper printout, paper tape, or CRT visual I/O. Permanent or temporary datasets and/or files can be created on these devices. All such options and features are under the control of any one of the BCI Monitor system users. With the ability to run any and all types of subtask programs, the Monitor's data analysis protocol can be tailored to any user's requirements. A user can add new analysis programs (i.e. run any processing program as a Monitor subtask) and control all operations completely, utilizing the informative displays and powerful system command functions of the Monitor.

Thus, in general, the Monitor serves as a sophisticated data port which has processing, analysis, and control features built in. Through the use of Monitor and its various

applications/systems subtasks, data collected at other installations can be quickly and efficiently processed, and results obtained, with all operations under detailed user scrutiny and supervision.

SUPPORTIVE ANIMAL STUDIES-UNIVERSITY OF IOWA

A. INTRODUCTION

The first objective of the present research is to assess the behavioral relevance of neural functioning in the peripheral part of the visual system in rabbit by investigating whether the electroretinogram (ERG) can be bidirectionally conditioned by operant procedures. If, as is likely, the occurence of discrete changes in a segment of the ERG waveform can be brought under the control of reinforcement, then a second objective would be to determine how those changes are regulated by efferent innervation to the retina by attempting to condition the ERG of rabbits whose optic nerves have been sectioned. It is hypothesized that retinal sensitivity as reflected in the ERG is controlled in part by higher nervous centers which exert their effects through centrifugal innervation to the retina and further that the interruption of these inputs will preclude modifications by operant conditioning.

Recent research has demonstrated that the operant technique is effective in conditioning bioelectric events within the brain (Wywricka & Sterman, 1968; Fetz, 1969; Black, 1971). Systematic studies in cat conducted in this laboratory have shown that the operant procedure can change components of the waveform of the early and late components of the visual cortical evoked potential (Fox & Rudell, 1970) and of the spontaneous EEG (Ahn, 1979). Even the early segments of the visual evoked potential can be operantly conditioned (Rudell & Fox, 1972). Since the early segments have lower variability and are more dependent on stimulus parameters than on state variability, it seems reasonable to expect that the ERG, which reflects the behavior of neurons in the retina, can be brought under operant control. The control of

the retina by the brain is presumed to operate via a centrifugal system of retinal innervation which is capable of biasing retinal sensitivity and of determining the nature of the information transmitted. Thus, the sensory system to some degree would be subject to purposive central control.

There is considerable evidence, both anatomical and physiological, for the existence of such a centrifugal system. Observations of apparently efferent fibers within the retinas of several vertebrates have been reported by anatomists (von Monakow, 1889; Ramón y Cajal, 1894; Dogiel, 1895; Arey, 1914; Polyak, 1941; Brooke, Downer & Powell, 1965; Honrubia & Elliott, 1968; Honrubia & Elliott, 1970) but as Ogden (1968) notes in his review of the anatomical and physiological evidence, the existence of efferent retinal fibers remains inconclusively demonstrated in several species. However, anatomical evidence does provide a firm basis for assuming that centrifugal fibers do exist in the rabbit retina. Those fibers have been described to radiate from the optic nerve head to the periphery of the eye and to end on the ganglion cells and in the inner plexiform layers (IPL) (Ventura & Mathieu, 1959). The exogenous origin of the efferent fibers in the rabbit retina was also suggested by their course from the ganglion cell layer to the outer layers and their thinning as they ran outward (Shkol'nik-Yarros, 1971). The fibers had varicose thickenings at equal distances and brush-like endings typical of endings of afferent fibers in other parts of the central nervous system. The difficulty in demonstrating centrifugal fibers in the rabbit retina with the Nauta method suggested that the centrifugal projection is probably not large (Cragg, 1962). An electron microscope study revealed myelinated fibers in the IPL of the rabbit (Luciano, Spitznas & Reale, 1971). The location corresponded to that of centrifugal fibers in birds. In addition, the fibers showed a positive histochemical identification for acetylocholinesterase as

is usually found in efferent fibers (Reale, Luciano & Spitznas, 1971). At the level of the retina, then, anatomical work provides good evidence for centrifugal fibers in the rabbit retina.

Centrifugal influence seems to be realized through the amacrine cells. Observations in several species indicate that the centrifugal fibers terminate around the amacrine cells of the retina (Cowan, 1970; Byzov & Utina, 1971; Shkol'nik-Yarros, 1971) and probably regulate the output of these cells. According to Dowling (1970), the synaptic connections of the amacrine cells permit them to influence the bipolar cells, the ganglion cells, and other amacrine cells. Thus, amacrine cell processes appear "well suited to mediate lateral and reciprocal interactions between adjacent neurons" (Dowling, 1970).

In mammals the site of origin of the centrifugal fibers and its possible relationship to the superior colliculus has not been established. However, the superior colliculus, thalamus, and midbrain have been suggested as possible sources of the centrifugal projection (Cragg, 1962). In the avian brain there is a well-organized projection of the optic tectum on the isthmo-optic nucleus, the nucleus from which the centrifugal fibers originate (Cowan, 1970). If, as is likely, a similar connection exists in mammals, then such a projection from the superior colliculus to the cells of origin of the centrifugal fibers would provide the necessary link between the centripetal and centrifugal parts of a feedback mechanism acting on the retinal neurons. Since visual and other cortical areas project to the superior colliculus (Brook, Downer & Powell, 1965) the activity of the retina would be subject to cortical influence. The existence of centrifugal connections would permit attention, habituation, and conditioning to influence the processing of visual information in the early stages of sensory integration (Palestini,

Davidovich & Hernández-Peón, 1959).

Little is known about the functional significance of centrifugal fibers to the retina but there is considerable speculation that they modulate the flow of information through the retina. The functions of centrifugal fibers may differ in different species though there may be some overlap in function as well. Centrifugal interference in sensory systems would act to increase the flexibility and information processing capability of the systems. The actual synaptic mechanism seems to be one of active inhibition in most sensory systems (Livingston, 1959). In the retina, centrifugal input seems to modulate rather than evoke visual responses. This modulating role is strongly suggested by the finding that electrical activation of the isthmo-optic tract in the chick does not evoke firing in retinal ganglion cells in the absence of visual stimulation (Miles, 1972).

Centrifugal retinal innervation may allow an animal to increase or decrease retinal sensitivity according to needs provoked by environmental circumstances. As Miles (1972) has noted, dark adaptation provides a long-term solution for an increase in retinal sensitivity under conditions of low luminance but is of little value in coping with transient changes in luminance. The centrifugal system might offer a "dynamic solution" whereby retinal sensitivity is increased to serve such purposes as allowing "local adaptation in shadowed areas of the visual field" (Miles, 1972). Evidence supporting this hypothesis was obtained in a behavioral study of the visual system of the chick (Rogers & Miles, 1972).

Physiological studies of centrifugal input have examined the effects of brain stimulation or optic nerve stimulation on retinal ganglion cell firing. In cat, collicular and mesencephalic reticular formation stimulation resulted in both facilitatory and inhibitory effects on retinal ganglion cell firing

(Granit, 1955). Since these effects were different from those resulting from antidromic activation, they were interpreted as centrifugal in nature. That interpretation was substantiated by a study in rabbit in which centrifugal impulses were distinguished from antidromic impulses in the retina by shocks applied to the contralateral optic tract (Dodt, 1956). A retinal spike was elicited which was delayed relative to antidromic spikes. It was concluded that the delayed spike is evidence for a centrifugal effect on the retina recorded after its having traversed one or several synapses.

There is also some evidence that extravisual stimulation may influence retinal activity (Palestini, Davidovich & Hernández-Peón, 1959). In rabbit, Sokolov (1960) found that the orienting reflex influenced the ERG to high-frequency light stimulation. With an auditory stimulus, there was an increase in the reaction to high-frequency stimulation and the shape of the ERG was changed so that the latency of the b-wave peak was decreased, suggesting a shortening of the cycle of excitation in the ERG. In cat, optic nerve responses were evoked by auditory and somatic stimulation (Spinelli, Pribram & Weingarten, 1965), an observation which suggests activation of the retina by centrifugal fibers. Other investigators have presented alternative interpretations to that finding, namely volume spread from other structures (Ogden, 1968) and spread by ephapsis or the action of axo-axonal synapses (Brindley, 1970). The finding of Mascetti, Marzi, and Berlucchi (1969) that after unilateral cervical sympathectomy auditory stimuli affect the contralateral but not the ipsilateral optic tract suggests that the influence on the retina of arousal by auditory stimuli is conveyed by sympathetic fibers (Brindley, 1970). It should be noted, however, that Spinelli, Pribram, and Weingarten (1965) also found that flashes preceded by a click produced progressive inhibition of the ERG b-wave. Furthermore, it has been found that activation of centrifugal

fiber pathways by nonvisual sensory inputs also modify the firing pattern and receptive fields of single retinal ganglion cells (Spinelli & Weingarten, 1966; Weingarten & Spinelli, 1966; Branston & Fleming, 1968).

Under the assumption that centrifugal input modifies retinal sensitivity, various investigators have looked at the effects of optic nerve section and subsequent drug administration on the ERG but neither of these types of studies has produced conclusive results. One difficulty in most of these studies is that possible vascular damage to the retina may account for observed ERG changes. Jacobson and Gestring (1958) observed that the amplitude of the ERG increased following optic nerve section in cat and monkey and that alteration in ERG amplitude which usually follows injection of various drugs did not occur in denervated eyes. These findings have not always been substantiated by other workers (e.g., Brindley & Hamasaki, 1962). Administration of Nembutal led to an increase in the amplitude of the ERG of the chick in normal but not denervated eyes (Scholes & Roberts, 1964). Ogden (1968) suggested that the failure of the Nembutal to have an effect after denervation resulted from a reduction in intraretinal drug concentrations consequent to vascular damage to the retina. Studies of the effect of optic nerve section on the rabbit ERG have also produced equivocal results. One study revealed no differences in ERG two to seven months after unilateral transection of the rabbit optic nerve. In that study injection of sodium pentobarbital produced an enhancement of the a-wave and b-wave in both normal and denervated eyes (Winkler, 1972). In another investigation, optic nerve section in rabbit led to an immediate depression in ERG amplitude which was gradually restored to normal amplitude, where it remained for several months (Mita, Suzuki, Nikara & Ogawa, 1962). This finding is inconsistent with that of Abe (1962) who found that either intracranial or intraorbital section of the rabbit optic nerve resulted

in an increase of the ERG b-wave to a value up to 330% of its original amplitude and then decreased to 200-250% within twelve hours after the lesion. In contrast, Borg and Knave (1971) observed a small increase in ERG amplitude immediately after optic nerve section in rabbit which remained constant for eight months. Twenty-two months after transection the amplitude decreased. The authors attributed the initial increase to absence of centrifugal activity and a concomitant heightening of retinal excitability and the final decrease to retrograde degeneration in the retina. Other investigations on the effects of retinal denervation suggest that centrifugal input plays a role in the ERG recovery cycle (van Hasselt, 1969; van Hasselt, 1972). The majority of the findings on the effects of optic nerve section on ERG suggest that centrifugal activation exerts a tonic inhibitory effect on retinal activity.

It should be noted that even in pigeon where the centrifugal connections to the retina are well known, denervation of the retina has not produced consistent results. In one study, profound changes were found in the local ERG following denervation (Ogden, 1968). The a-wave and b-wave were unchanged but the off-responses were greatly exaggerated and low-voltage oscillatory potentials appeared during retinal illumination. No such changes were observed in another study in which denervation appeared to slow the time course of the ERG (Galifret, Condé-Courtine, Repérant & Servière, 1971). Miles (1972) found, however, that there is an increase in retinal excitability following the passage of a dark edge advanced through the visual field which is abolished by cooling the isthmo-optic tract. This observation is in accord with his hypothesis that the centrifugal system provides local adaptation in shadowed areas of the visual field.

Sectioning the optic nerve and observing its effects on ERG amplitude therefore, appears to be a limited method for elucidating the function of

efferent innervation to the retina. Vascular damage may introduce biasing effects which may be responsible for the time course of recovery. Furthermore, comparison among studies is difficult since the ERG changes which are observed are dependent on the method of testing. The nature of the stimulus (e.g., single or double flashes), the intensity of the stimulus, the width of the interstimulus interval, the amount of dark adaptation, and the presence of an anesthetic are some of the many factors which can influence the type of ERG change observed. The powerful technique of operant conditioning used in the present experiment avoids previous inadequacies by examining the extent to which the modifiability of the ERG is affected by by optic nerve section.

B. RATIONALE

Present research is investigating the modifiability of discrete segments of the ERG waveform by operant conditioning procedures under the hypothesis that retinal sensitivity is regulated by efferent innervation. The behavior of retinal neurons, as reflected in the ERG, will be modified by techniques already demonstrated in this laboratory to be effective in cortical conditioning (e.g., Fox & Rudell, 1970). Previous studies concerned with the functions of the retinal centrifugal system have been inconclusive partly because the methods of those studies did not allow access to specific, reversible, bidirectional changes in ERG. The present technique of operant conditioning, on the other hand, offers a paradigm whereby discrete segments of the ERG waveform can be selected and subjected to bidirectional manipulation with appropriate reinforcement. The major experiments are being conducted in rabbit, a choice consistent with the methodological requirements of minimal eye, head, and body movements.

The immediate aim of the present program is to determine those particular segments of the ERG which can be modified in a reinforcement paradigm. Low-probability segments of the ERG waveform are chosen and the animal reinforced for producing those waveforms which meet a pre-specified shape and amplitude. Since the ERG is a summed response representing the activity of different retinal neurons with different spatio-temporal patterns, then determining the segments of the waveform capable of modification may shed light on the question of the origins of its components (a-wave, b-wave, etc.) within the retinal layers. The second aim of the study deals directly with the question of the role(s) of efferent innervation by assessing ERG conditionability after optic nerve section. The demonstration that the ERG cannot be conditioned after optic nerve section would provide additional clear-cut evidence corroborating anatomical and physiological investigations that suggest higher centers control retinal sensitivity.

C. OPERATIONAL TECHNIQUES

An on-line computer experiment is being used for conditioning the ERG in rabbit. The methods and techniques utilized in these experiments can be conveniently presented within the following categories: (1) animal preparation; (2) stimulating and recording techniques; and (3) conditioning procedure and computer programs.

1) Animal preparation

Experiments are being carried out in adult albino rabbits. In separate experiments, two types of reinforcement are being explored: water reinforcement and rewarding brain stimulation. The rabbit tolerates water deprivation well and the water reinforcement is consumed with minimal head and mouth movements since it is introduced directly into the mouth through a fistula in the rabbit's cheek. For electrical stimulation of the brain,

stainless steel electrodes are chronically implanted stereotaxically (Sawyer, Everett, & Green, 1954) in the posterolateral hypothalamus, a site which has been demonstrated to be positively reinforcing in rabbit (Bruner, 1956).

The nictitating membranes of the rabbits' eyes have been removed under xylocaine anesthesia. Under sodium pentobarbital anesthesia, a fistula was made in the rabbits' cheeks for delivery of the water reinforcement. For each rabbit a small hole was made in the left cheek by means of a leather punch. A short length of PE-240 polyethelene tubing, heat flared at one end and positioned against a polyethelene washer (8 mm. OD), was passed from the inside of the oral cavity through a hole in the cheek. The tubing projecting from the cheek, after having been fitted with a second washer, was heat flared against the external washer. The cannula is thus held firmly between the inner surface of the oral cavity and the outer cheek. Tygon tubing, connected from the output spigot of a solenoid valve and water reservoir, carries the water to the conditioning chamber where the Tygon tubing terminates in a blunted hypodermic needle which is inserted into the cannula. During the course of the experiment rabbits are maintained on a water deprivation schedule of approximately 90 cc. per day.

For the experiment the rabbit is restrained in a specially designed plexiglass holder which prevents head and body movements (e.g., Mitchell & Gormezano, 1970). Foam-covered adjustable plates, between which th rabbit's ears are secured, allow the rabbit's head to be maintained in a fixed position. An additional plate to the rear of the rabbit's body is adjusted to secure the rabbit in the holder and prevent body movements.

Tetracaine is used to anesthetize the cornea of the rabbit. Pupils are dilated with Mydriasil and Artificial Tears are used to promote good contact with the corneal electrode used to measure ERG.

For optic nerve transection, rabbits are anesthetized with sodium pentobarbital and the orbit is infiltrated with xylocaine. An incision is made at the superior margin of the cartilaginous layer around the supra-orbital ridge. After Tenon's capsule is opened, the superior rectus is transected and the supra-orbital ridge removed to expose the optic nerve. The nerve is cut and care taken not to damage the retinal blood supply.

2) Stimulating and recording techniques

In separate experiments, both single and double flashes are presented to the rabbit eye with a Grass PS2 photostimulator which has a flash duration of approximately ten microseconds. A Burian-Allen speculum contact-lens electrode especially constructed for use with adult rabbits is used for ERG recording and biominiature electrodes applied to the skin near the internal and external canthi of the eye are used to record eye movement. The output of Grass P511 amplifiers used to amplify the signals is monitored on a Tektronix 502 oscilloscope. Incoming waveforms, average waveforms, and the difference between them are displayed on a Tektronix oscilloscope connected to the computer. In experiments in which rewarding brain stimulation is used for reinforcement, appropriate electrical stimulation is provided by a Grass S4 Stimulator.

3) Conditioning procedure and computer programs

The entire conditioning procedure is under the on-line control of a PDP-8 computer. The procedure of the conditioning is similar to that previously used in this laboratory (Rosenfeld, Rudell & Fox, 1969; Fox & Rudell, 1970; Rosenfeld & Fox, 1971; Rudell & Fox, 1972). Recording and training is carried out in the upper berth of an upright freezer shell divided into two berths. The inside of the berth is painted white and dimly lit to provide low-level background illumination. The internal dimen-

sion of the berth is 2 ft. x 2 ft. x 2 ft. Centered on one wall is a 13 inch x 13 inch window through which light stimuli are presented. The Grass PS 2 photostimulator head is mounted on the freezer shell and aimed through the windows into the box. The rabbit in the holder is oriented in a fixed position with respect to the photostimulator head. A fan continuously circulates air inside the recording chamber. The window in the freezer is covered with copper screening and the shell itself is connected to ground to provide electromagnetic shielding in the recording area.

Rabbits are first run without reinforcement to establish baseline values for selected criterion segments of the ERG waveform. Training for waveforms one standard deviation above or below mean waveform segment values are then initiated and continue until waveform shaping is obtained. Approximately four hundred trials, broken down into blocks, are given each day. After training several days of non-reinforced extinction follow. The procedure is then repeated for training in the direction opposite to that of the initial training.

Two computer programs are being used, the first of which allows, by means of the teletype keyboard, the parameters for the particular experiment to be typed in. The computer triggers the photostimulator at specified intervals and then samples the A-D at regular time intervals. These values are stored in memory and displayed on a storage oscilloscope as an average waveform. Low-probability segments of the waveform are chosen and windows set for a criterion waveform. The criterion wave is a discrete wave segment of the ERG used as the experimental parameter. Twelve parameters describe the criterion wave. Three windows with four sides each measure twelve parameters from the base to the apex and back to the base of the waves. The sizes of each window are able to be adjusted with regard to the time base and amplitude. Also, the time bases and amplitudes among the

three windows are able to be altered. The second program controls the conditioning procedure itself by looking for criterion waveforms and monitoring eye movement potentials. The computer activates reinforcement delivery if the presence of a criterion waveform occurs in the absence of eye movements during the sampled segment.

During the experiment data is stored on digital magnetic tape and later analyzed at the University Computer Center. The tape preserves each analog response along with summary information about the trial. The number of successes and the means and standard deviations for each of the components are printed out and the criterion and non-criterion waveforms plotted. The effect of the conditioning procedure is evaluated by comparing the performance of the animals during the latter blocks of training with their performance during non-reinforced baseline and extinction. Each of the parameters can be analyzed in a treatments-by-subjects design, with baseline training and extinction as the treatments. From the analysis of variance, values of t can be computed to compare the reinforced and non-reinforced blocks of trials.

D. SUMMARY OF RESULTS

All of the operational techniques discussed in Section C have been developed. In addition, appropriate parameters of light stimulation and background illumination have been worked out to provide a constant level of dark adaptation throughout the experiment. This was necessary to assure that fluctuations in the ERG are due to internal variability rather than to environmental variables which affect dark adaptation.

Five rabbits have been run using the first computer program to establish baseline values for selected criterion segments of ERG waveform. In order for a response to be able to be operantly conditioned, it must show

some variability. We have found that even with a pre-conditioning series of flashes which slightly reduces variability, ERG components show variability sufficient for the utilization of the operant procedure. It can be noted that, under carefully controlled stimulus conditions, b-wave amplitudes in humans and rabbit have been shown to have day-to-day variability of as much as 95% (Spivey & Pearlman, 1963). Other observations of ERG variability have also been published (Ercoles & Ronchi, 1962; Ronchi & Freedman, 1964; Knave, 1970; Ronchi & Salvi, 1971; Lawwill, 1972).

A variety of technical difficulties interrupted the experiments as the collection of the baseline data was nearing completion and training was about to commence. The most important technical problem is a malfunctioning tape deck. Due to the delay of contract funds, the tape deck remains in need of repairs. ERG training cannot begin until the tape deck is restored to working order. The solution of other technical difficulties was also held up by the delay of contract funds. Included among items requiring repair were Grass P511 amplifiers and a Grass PS 2 photostimulator. A new strobe flash was also needed.

In addition to obtaining the baseline data preliminary to the ERG operant conditioning study, other relevant studies have been initiated in our laboratory. The first of these is an attempt to replicate in rabbit the finding of Bogoslovkii and Semenovskaya (1959) that the human ERG can be classifically conditioned. In their study sound served as a conditioned stimulus and light was the unconditioned stimulus. Numerous pairings of the sound with a strong light led to an increase in the b-wave amplitude evoked by a weak light when subsequently paired with the sound. Our study is using a similar methodological procedure but includes proper controls (e.g., pupillary dilatation) not reported by Bogoslovskii and Semenovskaya

(1959). Preliminary findings suggest that pairing the weak light with the sound after conditioning leads to a shortening of the ERG latency.

In another study we are looking at the effects on ERG of superior colliculus stimulation in rats. Since the superior colliculus is considered to be a possible origin of centrifugal fibers to the retina (Cragg, 1962) changes in the ERG waveform with superior colliculus stimulation would provide reliable measures of ERG. Twisted Nichrome wire electrodes have been chronically implanted into the superior colliculus of several rats. During testing the rats will be immobilized with curare and artificially respirated. The computer program to control the experiment has been written and is now in the process of being debugged.

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