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Electroencephalogram preferred frequency response signature to skilled motor functions

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THESIS

ELECTROENCEPHALOGRAM PREFERRED FREQUENCY RESPONSE SIGNATURE TO SKILLED MOTOR FUNCTIONS

by

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by

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TABLE OF CONTENTS

LIST OF FIGURES

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My love and thanks go to Carol for making this all possible.

I. INTRODUCTION

Man has managed to produce complex systems. He has been the originator of thoughts which have yet to be implemented. History is a compilation of challenges and thresholds which have been encountered, explored, and exploited by mankind. The Bioengineering Team, under the tutelage of Professor George Marmont, has been engaged in the research of the greatest unknown of all, the human brain.

A. BIOENGINEERING EEG RESEARCH

Continuing research, in the field of human electroencephalogram (EEG) analysis, has been conducted by the Bioengineering Team at the Naval Postgraduate School since 1972. The main thrust of our efforts has been in the direction of developing some correlation between subject tasking activities and resultant characteristic or preferred frequencies. Inseparable from this project development is the utilization of state-of-the-art electronics for tasking systems implementation as well as the creation of sophisticated computer programs to permit timely data collection and analysis. As an aid, computer modeling has provided us with an insight into the complexities of neuronal circuitry. Despite the vast amount of information collected from the central nervous system (CNS) of man and laboratory animals, fundamental questions of how the CNS functions are still mostly theory and guesswork.

The ultimate goal is to resolve the myriad of electrical

signals present in the brain into meaningful information, rendering it available for application in a knowledgable form to be utilized in a great many fields. Individuals could be examined for their trainability in areas requiring certain types of mental and/or physical activity. Biofeedback systems could be developed which would enable individuals to maintain a required state of alertness. Stress and fatigue monitors could provide critical information on an individual's ability to perform his assigned task in an acceptable manner. Preventative and correctional medical techniques would be vastly improved.

B. OBJECTIVES AND CONTRIBUTIONS OF THE AUTHOR

It is the intent of this research to examine task related preferred frequencies. Past results in this area will be critically examined. When thought to be necessary, new data will be collected to assuage any doubt as to the findings. Further investigation will be conducted into the cortical locations at which tasking evokes responses, and the preferred frequencies of the evoked signals. Analysis of data will be performed in determination of the effect biofeedback has upon task performance. Determination of the presence or absence of a task related response signature, under varying task conditions, will be made. Research results will be presented in an effort to relate different cortical areas to the response signature. Response signature characteristics will be defined in an effort to further improve the data collection, display, and analysis techniques.

The author has studied the data results from earlier research and has made a significant contribution through the detailed analysis of recently collected data. The results

of thorough EEG analysis have assisted in the development and modification of computer analysis routines. The author developed a computer model of the "Reverberating Circuit", which has already been presented in Reference 7. As the primary subject for recent investigations, the author has been the source of information for the correlation of subject response to the resultant processed electroencephalogram signals.

II. NEUROPHYSIOLOGICAL CONSIDERATIONS

A. ELECTRICAL ACTIVITY OF THE BRAIN

The development of cellular membrane potentials provides the foundation for electrical activity in the brain. The fluids within and outside of the cells of the body are electrolytic solutions. The solution outside the cell is rich in sodium ions and the solution inside the cell is rich in potassium ions. At rest, a very small electrical potential exists. The potential then rapidly drops (reversal potential) because of a rapid outflow of sodium and inflow of potassium through the membrane. The resting potential is approximately -60 to -80 millivolts (mV). If the electrical and/or osmotic balance of the nerve cell is sufficiently disturbed, an action potential of about +50 mV is generated. Sodium ions are transported into the cell while potassium ions are transported out of the cell.

The initiation of an action potential is dependent upon the ability to raise the excitatory postsynaptic potential (EPSP) to threshold potential which lies 10-20 mV above the resting potential. Normally, a spatial or temporal summation of EPSP's is necessary for the initiation of an action potential at the axon hillock of the neuron.

1. The Neuron

The neuron or nerve cell is the primary unit of the

vast network of the brain. From sensors, to processors, to the motor unit, signals race through nerve fibers at velocities ranging from 0.6 to 120 m/s [Ref. 9]. The neuron rests in a plasma membrane which is between 50 and 150 angstroms thick. The soma of the neuron is approximately 20 microns across. Axon length ranges from 50 microns to a meter, and axon diameter varies from 1-10 microns. The neuronal population is a matter for some speculation and varies from source to source. 2.5 cubic mm of the cerebral cortex might contain as many as 60,000 neurons [Ref. 12].

Inputs to the neuron may occur at many locations on its surface, but the primary locations are on the dendrites. The dendrites branch to form dendritic trees. There can be inputs from 2000-4000 cells to one neuron. The output of the neuron, called an action potential, travels away from the neuron along a "transmission line" called the axon. The action potential starts at the axon hillock. The action potential from this one neuron may be transmitted to as many as 600 other neurons [Ref. 12].

The connection between one neuron and another is called a synapse. In the 2.5 cubic mm mentioned above, there can be 3 billion synapses. The presynaptic terminal contains vesicles which are the synaptic transmitters. The presynaptic terminal emits either an excitatory or an inhibitory transmitter into the synaptic cleft. When an excitatory transmitter is released into the synapse, permeability changes result in decreased electrical potentials or depolarization. The result is called an excitatory postsynaptic potential. Hyperpolarization is caused by the release of inhibitory transmitters into the synapse. We refer to this change in potential as an inhibitory postsynaptic potential.

The description of individual neurons as the

elementary level of electrical excitation must naturally be followed by an attempt to explain the summation of approximately 7 billion such units in the cerebral cortex. The resultant signals are only partially understood. We know that individual neuron action potentials cannot be detected at the scalp. It seems likely that signals related to a task objective would be the result of the simultaneous activity of large numbers of neurons within the cortex.

B. MEMORY

Guyton has classified memory as follows [Ref. 4]:

* Sensory
* Short-term or primary
* Long-term
  - Secondary
  - Tertiary

Sensory memory is the foundation of the memory process. There is a sensory collection, either consciously or subconsciously, from our surroundings. These signals may be processed in any number of ways. Four possibilities are: 1) not processed as perceptual signals (discarded), 2) retained for short-term memory, 3) retained for short-term and transferred to long-term memory, 4) retained for long-term memory.

Short-term memory refers to those signals which can be recalled for some function over a period lasting from a few seconds to 30 minutes or more. One of the methods by which short-term memory might be established is based on the "Reverberating Circuit Theory". An area excited by the

tetanic stimulation of a neuron continues to emit rhythmic action potentials until the synaptic transmitters exhaust themselves.

Functions can be reproduced or called from long-term memory for periods from a few hours to a life time. The duration of recall is dependent upon the length and strength of the training or "fixation" period. We might expect that through repetition a short-term reverberating circuit becomes altered to such an extent that a long-term circuit becomes established. Circuit alteration might occur in the form of physiological changes in:

1. the number of presynaptic terminals,
2. the sizes of the terminals,
3. the chemical concentrations of the synaptic transmitters,
4. the permeability of the postsynaptic terminals,
5. the chemical reactions at the synapse.

C. CONTROL CF MOTOR FUNCTIONS

Since the task performed by our subjects in the EEG research is a skilled motor function, it is important to have some appreciation of the mechanism by which task accomplishment is achieved. The subject was seated with a control stick in his right hand. The stick governed the position of a dot on a CRO. The dot was perturbed both in magnitude and direction in a pseudo random manner. The subject was required to react to the dot displacement by bringing it back to scope center with his control stick as quickly as possible. It required a high degree of eye and

hand coordination. The eye perceived a moving target and the hand reacted to null or return the displaced target to its resting level. The task requires:

* visual acquisition,

* signal processing of sensory inputs,

* command signals to skeletal musculature,

* feedback and comparator signals for task accomplishment.

The visual processing center has different channels for pattern and motion perception. We were not interested in pattern recognition. But what of motion detection? Direction sensitive neural circuitry is one of the most acceptable explanations [Ref. 10]. This would complement our theories regarding memory. Specific circuits acclimate themselves to a given direction in much the same manner as we saw in long-term memory. These circuits lie in the lateral geniculate body as well as the visual cortex. Reference 8 amplifies on direction sensitive circuitry and the phenomenon of lateral inhibition. As an individual becomes accustomed to the detection of certain types of target movement, we say that he has become trained. In our task, the trained subject has the knowledge of what target to expect. He also knows from where he can expect it to appear. This allows the subject to detect the motion more quickly. It is also quite probable that the motor regions of the cortex will react accurately and more quickly with less and less visual sensory information as training progresses. This is accomplished by an extrapolation or fabrication process in the visual processing areas [Ref. 10]. The sensory signal has progressed from the eyeball, along the optic nerves to the chiasm and then radiates to the pretectal nuclei of the brain stem as well as to the lateral geniculate body and the occipital regions of the

cortex. Knowledge of signal propagation characteristics within the brain is critical to the correct placement of electrodes and subsequent data analysis. The task related preferred frequencies pertain to motor control signal processing of the cerebral cortex. Selection of the proper frequency ranges assures us of collecting only those electrical signals which are desired. Visual association areas (mainly pyramidal cells) spread out from the primary visual cortex to cover what is known as the occipital lobe. The primary visual cortex (striate cortex) is believed to contain 10% of all the cortical neurons (mainly stellate cells) despite the fact that its surface area is only 3% of the cerebral surface [Ref. 12]. The result of extensive transmission is that we may record motor related visual processing signals. Since the task initiates a visual evoked response (VER), in addition to the task related response in the motor cortex, there is a wide spectrum of task related signal processing occurring throughout the cortex.

The motor-premotor areas of the frontal lobe are characterized by the large nunber (25,000-30,000) of giant pyramidal cells [Ref. 12]. This region is associated with skilled motor functions; for this reason, it has been a location of interest in previous EEG research. The giant pyramidal nerve cells are noted for the vertical extent of their dendritic extensions. These cells probably serve as the sites for some of the most elaborate neuronal interactions in the cortex.

1. The Cerebellum

The cerebellum acts as a comparator of the commands of the motor cortex and the sensed performance of the parts of the body. As the motor function is executed, the results

are being monitored by the cerebellum. A specific neuronal circuit, the Purkinje cell circuit, is attributed with the functional capabilities of a comparator network, gating command and sensory inputs to the cerebellum (Fig 1). The Purkinje cell takes the command from the cerebral cortex via climbing fibers while sensory inputs go to the granule cell via mossy afferent fibers. These fibers branch and sub-branch to terminate at cerebellar synaptic glomeruli. A glomerulus is a complex synaptic arrangement of mossy fiber, granular cell dendrites, terminals of Golgi cell axons, and often a Golgi cell dendrite. The granule cell sends an excitatory signal to the Purkinje while the basket cell sends an inhibitory signal. Lateral inhibition as well as a subtle clocking effect is evident in the granule-Golgi-basket-Purkinje circuit. The lateral inhibition filters and focuses a multitude of sensory inputs in order to sharpen the response to the area directly related with the sensory input. It is at this point that the Purkinje gates the inputs of command with the sensory inputs to an inhibitory output. The cerebellum (Purkinje) output signal is subsequently forwarded to the musculature via the internal nuclei [Ref. 4].

2. Learning a Skilled Motor Function

As the individual trains himself in the execution of a skilled motor function, he "learns". For a given motor function, certain neural circuits are utilized repeatedly. It is quite possible that neuronal changes, leading to learning, occur at that unit in the circuitry which gates the command and sensory inputs - the Purkinje cell (Fig 1). As the changes to the neural circuits, discussed in section II.B, advance with time and practice, more and more of the motor functions are directed from the cerebellum in direct response to the sensory inputs, with less and less command

inputs from the motor cortex, ie. memory (Fig 2). It appears that a great deal of "thought" goes into a given motor function. We know from experience, however, that many of our skilled functions occur from other than a conscious effort. More likely we would call them "instinctive", but this is an inadequate term for the description of what most probably occurs as a motor function of the cerebellum.

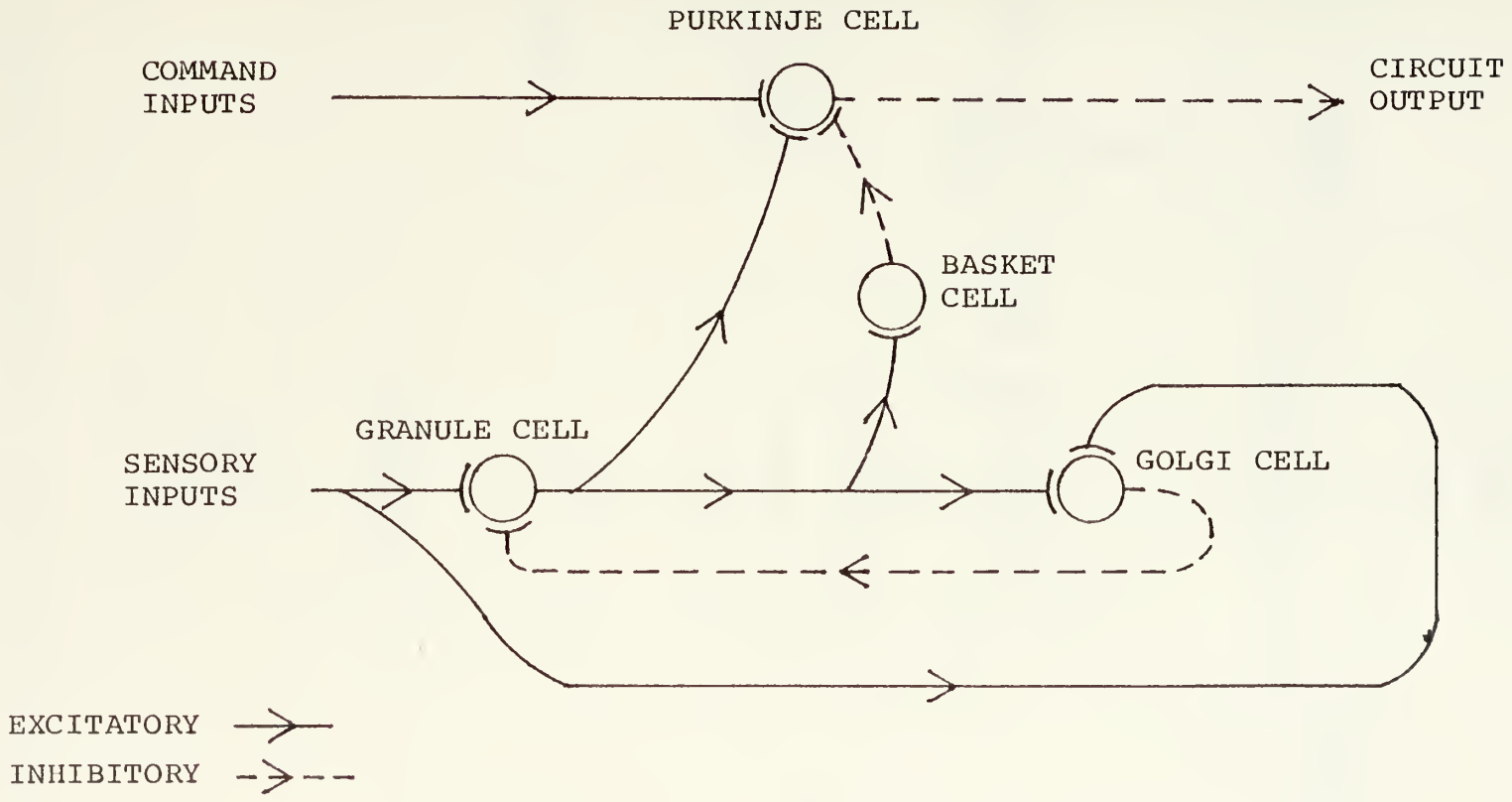


Figure 1 - THE PURKINJE CELL CIRCUIT

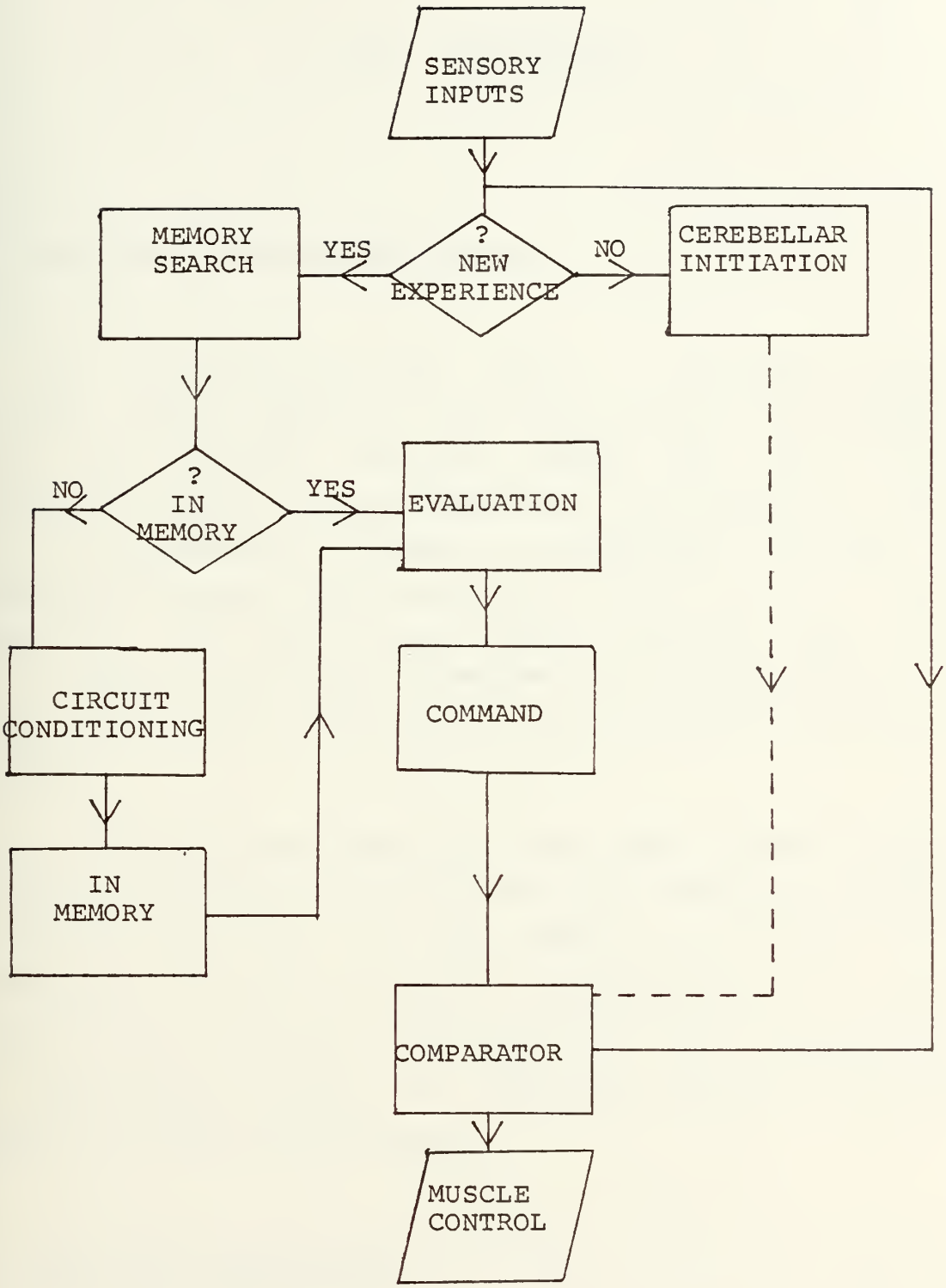


Figure 2 - CEREBELLAR INITIATION DUE TO TRAINING

III. BACKGROUND

A. THE HUMAN ELECTROENCEPHALOGRAM

The electroencephalogram (EEG) is the means by which electric signals within the brain are detected and measured. When the electrical activity reaches the scalp it has dropped to anything between zero and 100 microvolts [Ref. 4]. The equipment utilized in detecting, analyzing, and presenting the data which makes up the EEG must be quite sensitive. Not only are the signals extremely small, there are so many signals being processed in so many parts of the brain that we must be careful to pick up only those signals we want.

The electroencephalogram has been used to detect certain types of psychopathic abnormalities and degrees of cerebral activity. Emphasis has been placed on the presence or absence of alpha waves (rhythmic sinusiods of 8 to 13 Hz frequency). The alpha rhythm is associated with a relative state of calm inactivity. We have felt that investigation of frequencies related to mental and physical activities might be of more significance.

B. PREFERRED FREQUENCIES

The CNS operates on the transmissions of electrical signals at various frequencies. Certain frequency ranges

have been categorized as being characteristic of specific mental states. While it is expedient to indicate some of the categories, as described in the literature, we wish to make it quite clear that we have found certain categories to be of little use, if not inaccurate. From 8 to 13 Hz are the alpha waves. These are found in a resting or relaxed state and show the greatest amplitude in the occipital region. Beta waves are in the 14-25 Hz range. This category is further divided into beta I and beta II. Beta I waves are said to be inhibited by mental activity and beta II waves are reputed to appear only during intense mental activity. Beta waves are found primarily in the parietal and frontal regions. The Bioengineering Team has collected data which leaves little doubt as to the presence of task related mental activity (preferred frequencies) of greater than 30 Hz [Refs. 3, 7, and 11].

Frequencies which can be related to specific mental activities have been investigated by the Team for over four years. They have come to be called "preferred" frequencies. We have recognized for some time that there is an observable change in the EEG when going from a relaxed state to a skilled motor function task. There has also been some indication of frequency change under different tasking methods [Ref. 5].

C. TEGULAR ANALYSIS

Developed by Professor G. Marmont, tegulometric analysis is a highly sophisticated signal processing routine [Ref. 6]. Because of the low amplitude signals of interest and the relatively high noise environment in the brain, tegulometric frequency analysis is a powerful tool for the analysis of EEG data. The tegule is the resultant inverse

Fourier transform from the digitally filtered spectrum of raw EEG data. The tegule has the appearance of a spindle shaped envelope defined by a sinusoid of rising and falling amplitudes. The plots, to be presented, labeled "TWODET 70-95 Hz", show the EEG signals on traces 1 and 2. These traces are made up of tegules developed by signals in the 70-95 Hz preferred frequency region. Figure 6 is such a plot with a tegule annotated.

D. BIOFEEDBACK

Biofeedback (BFB) is a stimulus applied to the subject in our EEG research. BFB is generated by the processed EEG signals of the subject. Present research has utilized a white light behind a translucent screen as the stimulus. As seen by the subject, the BFB appears as a glowing wall of light. It varies in intensity from dark to a bright glow depending upon the mental activity of the subject. BFB is directly related to the task response signature addressed in this research, and its impact on the subject's performance will be analyzed.

E. TASK RELATED RESPONSE SIGNATURE

The cross multiplication of two tegular EEG signals results in a product which is a useful indication of cortical signal correlation. The product of two tegular sinusoids is the sum and difference frequencies. Reference 11 presents tegular examples of various frequency and phase relationships and their resultant products. The results gained by Wicklander and subsequent research projects have provided us with a background which has led to the present

techniques of synchronous detection. The concept of tegulometric analysis made possible this "running crosscorrelation". The cross multiplication trace of TWODET provides us with this capability of synchronous detection. Recent research work briefly pointed out a relationship between the task with which the subject was involved and resultant peaks along the cross multiplication trace. These product peaks were referred to as the "correlation response". It is this "correlation response" of synchronous detection which will be referred to as the "Response Signature" throughout this work (Fig 6).

F. MYOGRAMS

The electrical behavior of muscle fiber is very similar to that of a nerve fiber. The "twitch response" action potential of skeletal muscle can seriously confuse or completely overwhelm the normal EEG response. We have found that such actions as blinking, swallowing, jaw tightening; as well as involuntary muscle spasm, can make large portions of EEG data at least suspect if not totally useless. Figure 3 illustrates the myograms from one of our subjects.

The results of every EEG must be carefully examined in order to determine the extent to which myograms have overwhelmed the task related signals in the preferred frequency range of 70-95 Hz. Because of the broad band frequency characteristics of this strong pulse-like signal, there is no filtering technique presently available to eliminate these strong pulses. We have been very conscious of the possible presence of myograms and have made every effort to keep this noise from our data.

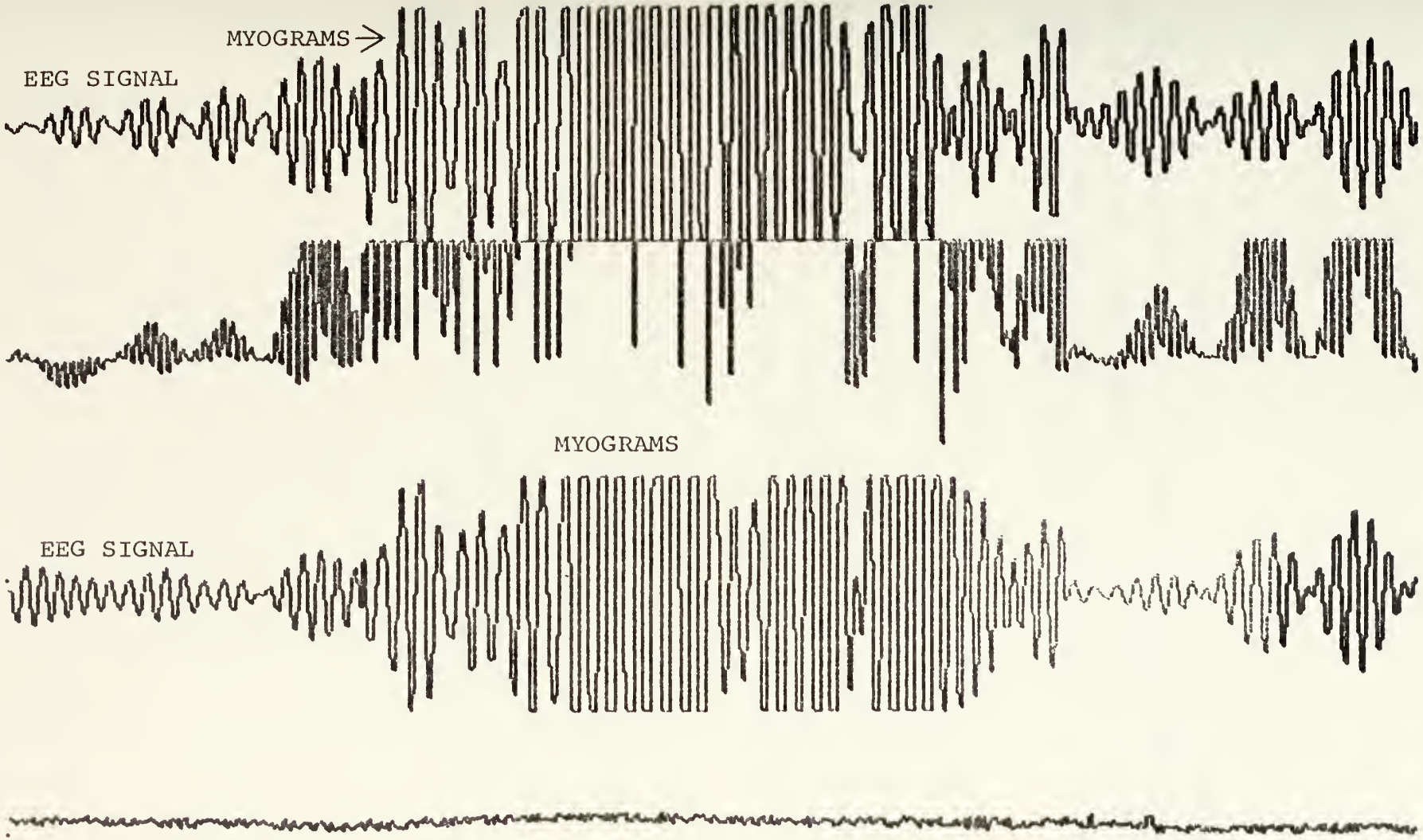


Figure 3 - OBVIOUS MYOGRAM PULSES

G. SUBJECT TASKING

In our investigation of preferred frequencies, the choice of subjects was an extremely important consideration. We found that the subject must be: (1) capable of accomplishing the task, (2) enthusiastic, and (3) able to provide a noise free EEG pattern.

Without task accomplishment, there was little consistancy in the results. The subject's response was more stress or crisis related. A trained or talented subject unable to enthusiastically participate would display the alpha rhythms of a relaxed individual. Certain subjects were found unsatisfactory due to excessive myograms.

The task was a relatively simple operation. Seated in a screened room, the subject controlled the position of a dot of light seen on an oscilloscope located approximately 1.5 meters in front of him. A control stick, similar to that in an aircraft, was the mechanism by which the subject controlled the dot. The tasking subsystem was developed last year and has been used for most of the EEG runs since then [Refs. 1 and 7].

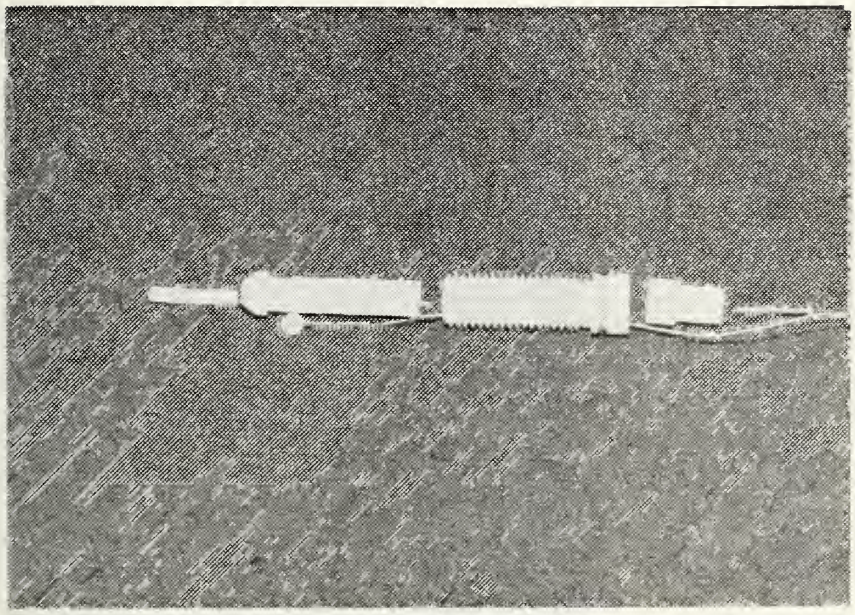
IV. EQUIPMENT USED IN THE RESEARCH

A. ELECTRODES AND HELMET

The Team has continued to use the specially mounted Beckman silver electrodes. A plastic retainer contains the electrode and the scalp contact, "Suca-bloc" (Fig 4). The retainer ensures firm contact between the electrode and the "Suca-bloc". While not in use, the electrode arrangement is suspended above a 0.15 molar sodium chloride solution with the scalp contact immersed. The effect is that we have an assembly which behaves as a silver/silver chloride electrode. To ensure optimum scalp to electrode contact, electrode paste, consisting of gelatinous sodium chloride, is applied to the scalp contact just before electrode placement.

Positioning the electrodes with some degree of accuracy upon the scalp is easily achieved by using the helmet constructed by the Bioengineering Team [Ref. 8]. The plastic electrode retainer, which is threaded, is screwed into one of 17 plastic disks about the helmet (Fig 5). Each disk has four positions into which the electrode retainer may be located. Each disk may also be rotated within its helmet position. There is virtually no location on the scalp which cannot be contacted.

B. THE DIGITAL COMPUTER AND ANALOG DATA CONDITIONING PERIPHERALS



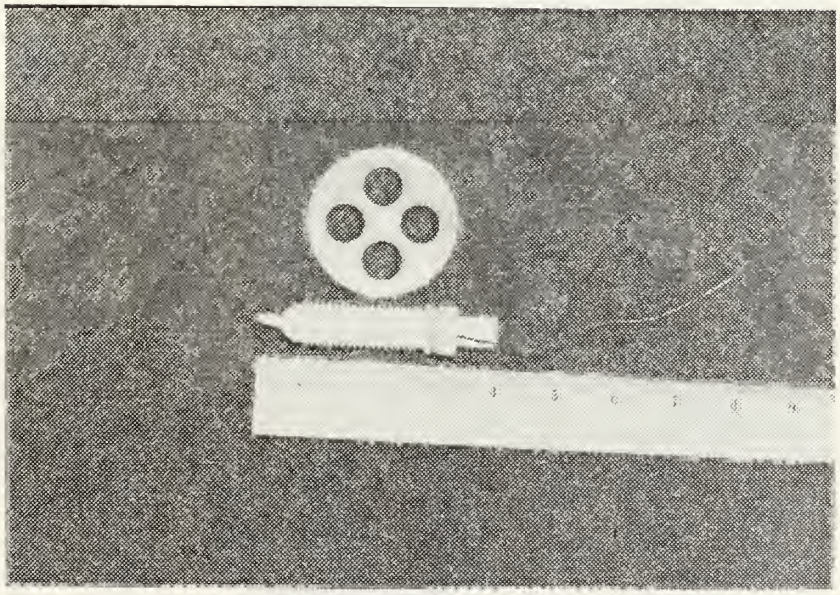


Figure 4 - ELECTRODES

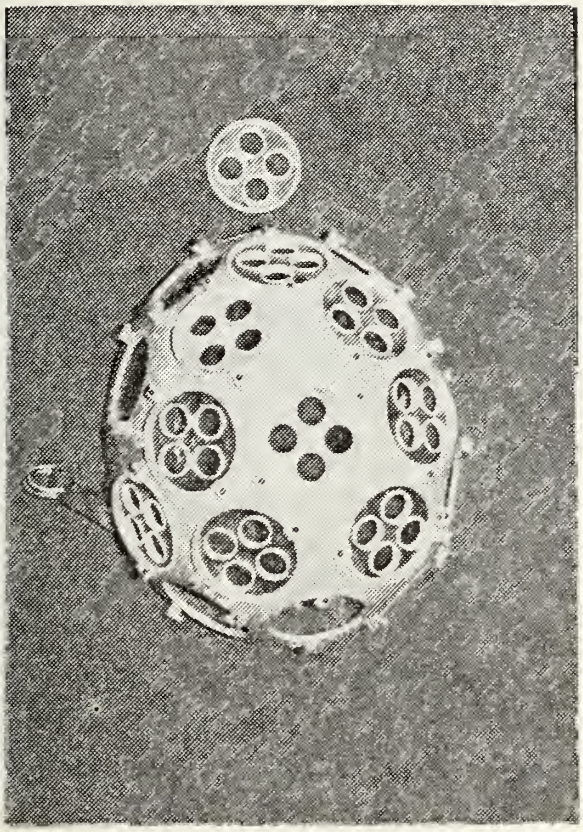


Figure 5 - ELECTRODE HELMET

We have used the PDP 11/40 and associated peripherals for the necessary data manipulation of EEG signals and the tasking peripheral indicator. Reference 2 provides detailed description of the data conditioning peripherals.

1. Eight Channel Differential Preamplifier: The preamplification of the raw EEG signals is accomplished at this point. Two amplification stages provide a common mode rejection ratio of 71.06 dB. The preamplifier generates a gain of 3850.

2. Anti-aliasing Filters: Four pole Butterworth filters are used. Filter response has been set 3 dB down at 256 Hz and 24.5 dB down at 512 Hz. A gain of approximately 10,000 is achieved across the preamplifier and filter stages. The gain from the two filter stages is 2.57.

3. Analog Conditioning Element (ACE): Analog to digital conversion of the preamplified and filtered EEG signals is performed by the ACE. In order to avoid phase delay between the eight channels, they are all sampled at once. The sampling rate is varied, as required, to afford the bandwidth of EEG data desired.

C. TASK RELATED PERIPHERALS

The subject is tasked by this peripheral system. References 1 and 7 provide detailed information regarding the components of this subsystem.

The tasking peripherals provide us with the ability to reproduce at will a number of variable tasks. The subject is seated in a screened room with a control stick in his

right hand and has a CRO display directly in front of him. The tasking subsystem generates a dot on the CRO which is perturbed in a pseudo-random manner. The rate of perturbation or dot displacement is controllable as is the magnitude of the displacement. In order to obtain about 35 perturbances per 100 s we would establish a slow clock rate of 1.5 Hz on the pseudo-random pulse module. A fast clock setting of 2.8 Hz will result in approximately 65 CRO dot displacements per 100 s to which the subject must react. A higher clock rate implies a more difficult task. In order to maintain a slower clock for ease of data analysis, while providing a task with a high degree of difficulty, we simply reverse the roll and pitch inputs to the CRO. With a reversed stick control, when you pull back on the stick the dot rolls sideways, and when you push the stick to the side, the CRO dot pitches up or down. The tasking subsystem is multivariable and reproducible.

The Performance Indicator Module has supplied us with the ability to accurately measure a subject's ability to perform the task. When the CRO dot was displaced, a task initiation mark was generated in order to mark the start of a task. The amplitude of the dot displacement was also recorded. The task initiation mark and subsequent displacement amplitude were inputs to our real time signal processing program (TWODET) as a "performance indicator". This was monitored on the display as seen in Fig 6.

D. THE BIOFEEDBACK PERIPHERAL

Feedback voltage, from the integrated cross multiplication product of TWODET, is amplified and transmitted to the light behind the translucent screen. The BFB light receives updated voltage levels every 0.25 s.

V. EXPERIMENTAL PROCEDURE

A. PRELIMINARIES

Approximately one hour is required to check the research related equipment and place the electrodes. The reason for this ultimately centered on our desire to achieve and maintain the lowest noise levels possible.

We had to insure that the pitch and roll control voltages remained a constant. Any fluctuations in this would have resulted in uncontrollable degrees of difficulty for the subject. CRO dot alignment at the control stick insured that, no matter what the magnitude of dot displacement, the subject would not lose the dot off of the CRO. Another control over the degree of difficulty was our careful setting of the tasking subsystem clock. This was accomplished with an HP 5304A Timer/Counter.

The areas of the scalp at which electrodes were to be placed were cleansed with ethyl alchohol, gently roughed, and then lightly coated with a 0.15 molar NaCl solution. In order to prevent the possibility of shorting two electrodes together, petroleum jelly was applied between the electrodes. This provided us with a barrier isolating electrodes to signal collection only at cortical areas of interest.

Each new subject had to be approached with the attitude that he shared little in common with other subjects. Skull

shape, hair distribution and density, emotional configuration, and physical condition all added to the complexities of a careful subject "suit-up". Once we had trained him and identified his quirks, the subject's preparation became routine.

Prior to each EEG the following variables were carefully recorded:

1. Subject's name,
2. Date,
3. Disk number (data storage),
4. Data collection computer program,
5. Digital filter parameters,
6. Electrode location,
7. Electrode resistances,
8. Tasking peripheral clock rate,
9. Disk address for each task run segment,
10. The task run scenerio.

B. COMPUTER PROGRAMS

1. Real Time Signal Processing

a. TWODET.SAV

Developed for the purpose of continuous correlation indication , TWODET collects, processes, stores,

and displays EEG signals on a real time basis. The result is simply a signal composed of the sum and difference frequencies which are multiplication products of the two sinusoidal EEG signals (tegules). TWODET remains as the most effective means for the synchronous detection of task related electrical activity in the brain.

TWODET takes the signals from as many as eight electrodes referenced against another electrode, usually placed on the fore-and-aft skull center line in the parietal region (vertex), and averages them. This average is then subtracted from the signals of two closely spaced electrodes respectively. These primary electrodes are the two which are gathering signals from the area of interest in the cortex. It is important to realize that the primary electrode signals are themselves included in the subtracted average.

The two difference signals are processed by the time to frequency discrete Fourier transform (DFT). The data is divided into four 0.25 s sections. Thus the data is displayed as a 1.0 s frame, but processed at 0.25 s intervals. Once in the frequency domain, only those spectrum components of interest are retained (70-95 Hz). Having been digitally bandpass filtered, the data is restored to the time domain via inverse Fourier transform (IFT). The resulting two individual signals are displayed as the first and third traces of a frame of data on the Tektronix storage oscilloscope (Fig 6). The data frames are displayed as the data gathering run is in progress. There is 0.25 s delay from point of collection to that of display. The second trace displayed represents the cross multiplication of the two primary electrode signals after they have been digitally bandpass filtered. The amplitude of this trace is a measure of the correlation between the two primary electrode signals. The integral of the cross

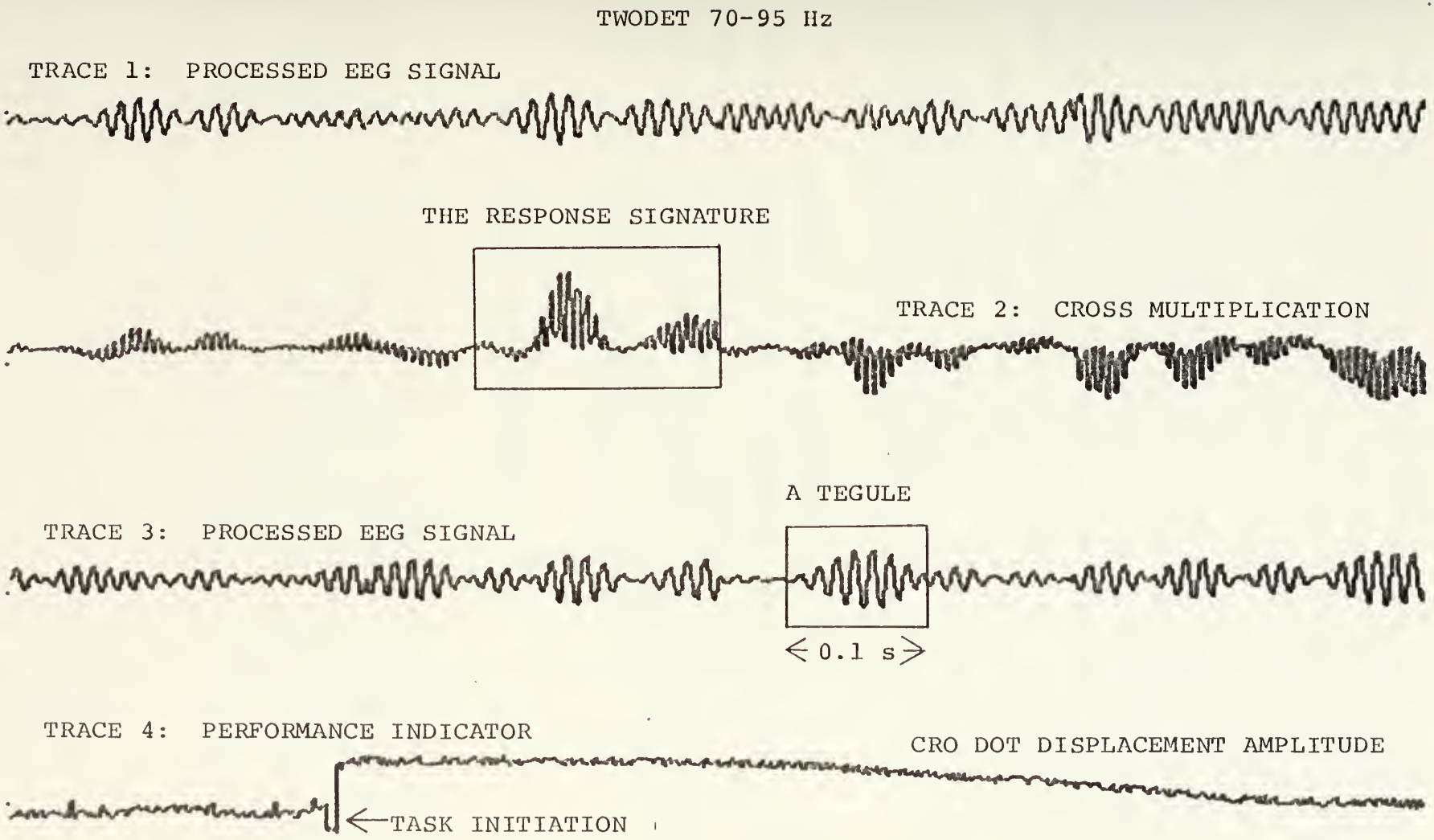


Figure 6 - TWODET DISPLAY

multiplication product is what determines the intensity of the BFB lighting system. If there is a high amplitude positive peak, the subject receives a bright glow from the BFB light. He will receive nothing from a zero or minus product, nor can he drive the BFB to brightness with myograms. The cross multiplication trace is also the location of the task related response signature. The fourth trace is simply the performance trace from the Performance Indicator Module (section V.C.) and is not processed by TWODET. A TWODET "run" can continue for as long as 600 s. The storage disk can hold no more than 600 s of data. A run was normally broken into six 100 s segments. The 100 s duration was chosen for subject comfort as well as allowing for six different task situations in one run.

TWODET is configured to take the primary electrode signals via channels one and two and the performance indicator via channel eight. To avoid confusion, we connect electrodes to channels of the same number (electrode 1 - channel 1). Channels 3, 4, 5, 6, and 7 are used for the secondary electrodes.

b. TWODET Modifications

In a continuing effort to improve our signal detection techniques, we have altered TWODET on several occasions. One such effort was quite successful. Instead of subtracting an averaged signal from the primary signals, we simply utilized only the primary signals. We have since returned to an average signal elimination in renewed efforts at noise rejection.

C. THE TRIAL RUN

As soon as the electrodes were in place and the subject was seated in the screened room, a standardization run was conducted. This usually took no more than two to five minutes with a trained subject. As much as five hours could be spent with a new subject. A new subject was usually somewhat apprehensive about the laboratory environment and had to achieve a satisfactory level of relaxation. Once relaxed, we had to establish that the electrode placement, on this new skull, was optimum. We chose the left motor - left premotor areas for primary electrode positions with the reference electrode at the vertex and ground electrodes on the mastoid (right and left). The secondary electrodes could be in any non-myogram related positions. This varied from subject to subject. Although the secondary electrodes could be as close as 2.5 cm to one another, we found that they should be no closer than 3.4 cm to a primary electrode. The primary electrodes were no closer than 3.2 cm to the reference electrode. These distances are constrained by our electrode helmet. Figure 5 illustrates the helmet electrode sites. Section VI presents the electrode positions for specific runs. We viewed the raw EEG data as well as the TWODET processed signals with the subject relaxed. Because of the abundance of recorded signals from this area, as well as the team's experience, it was relatively easy to see if the signals were typical or atypical. If the tegules were random in nature and free from myograms (no pulsing), we felt that to be typical. The cross multiplication trace had to have peaks (positive and negative) of medium to low amplitude evenly distributed about zero product. Figure 8 illustrates what we looked for in the trial run. The next step was to simply relocate the primary electrode leads to amplifier channels appropriate to the cortical region under examination. Recall that our primary electrodes were always connected to channels one and two. Unless absolutely necessary, electrodes were never physically relocated after

subject preparation. Electrode relocation was accomplished by interchanging preamplifier leads.

D. THE TASK SEQUENCE

Five primary electrode positions were investigated:

* Left Motor to Left Premotor,
* Left Motor to Left Occipital,
* Left Motor to Right Motor,
* Left Occipital to Left Occipital,
* Right Motor to Right Premotor.

At each of the five positions, the subject could be tasked in a number of different ways. The following task sequence was decided upon for the response signature analysis:

1. Relaxed, no visual stimuli

This was necessary to establish a baseline to which other data could be referenced. Without a good baseline, we found it useless to proceed. Examination of the amount of negative or positive correlation indicated by the cross multiplication in TWODET.SAV, as well as the raw EEG data, gave us indication of whether or not we had a good baseline. One of the most important aspects of the current EEG research has depended upon the positive or negative crosscorrelation resulting from the signal processing discussed in section V.B.1.a. We know from theory and practice that the resultant signal crosscorrelation from a relaxed subject should display a mean close to zero. Whether it is slightly positive or negative depends upon

electrode placement. Accordingly, we have developed a standard by gathering data from the subject in a relaxed state as a preliminary to each EEG session. From this standard we can evaluate subsequent runs on a relative basis. In the case of high positive or negative crosscorrelation from the relaxed run, we have had to determine whether the cause was equipment or subject related. We simply trouble shoot an equipment related cause. If the subject is the cause, the solution has been to get another subject or to train him into a state of relaxation.

2. Task with a slow clock and BFB

The task subsystem was used at a clock rate of 1.5 Hz (approximately 35 dot displacements/100 s). This rate allowed sufficient time between dot displacements so that the response to specific displacements could be analyzed. Biofeedback (BFB) was applied so that in later runs the absence of BFB could be comparatively studied.

3. Task with a slow clock and no BFB

This setup was the same as above except there was no BFB.

4. Task with a slow clock, BFB, and reversed control leads

We increased the level of difficulty by reversing the stick control signals. The purpose of this was to investigate a possible increase in positive correlation resulting from increasing degrees of difficulty at the same clock rate.

5. Task with a fast clock and BFB

The task system clock rate was increased to 2.8 Hz (approximately 65 dot displacements/100 s). Although data

analysis is much more difficult at this rate, it was felt that more information was needed relating task difficulty to the amount of positive correlation achieved.

6. Task with a fast clock and no BFB

We eliminated BFB for the purpose discussed earlier.

VI. PRESENTATION OF DATA

A. COMPUTER PROGRAMS

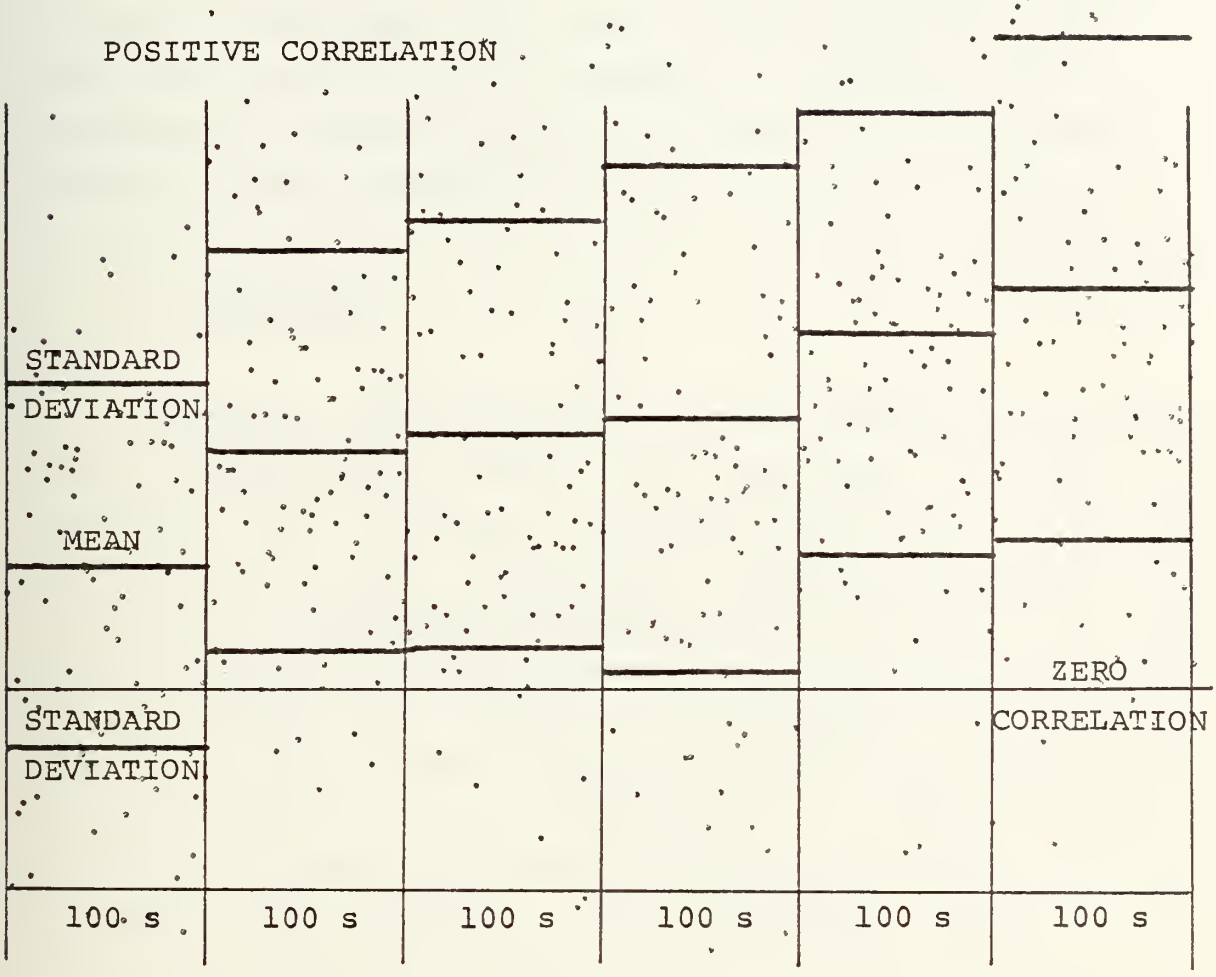
The REPLAY series of programs are those which we have used for the purposes of TWODET data review and analysis. Data is replayed from the disk and reviewed on the Tektronix storage CRO. Frames of data may also be plotted on the HP 7004B X-Y Recorder for detailed analysis and for permanent record. Due to the varied display and analysis requirements, a number of REPLAY programs have been written. Only those used by the author are addressed below.

1. REPLAY.VAR

REPLAY.VAR allows for a frame by frame replay of the processed TWODET EEG signals. The CRO display is identical in form to that seen while data collection is in progress. One of the callable parameters designates the period that a frame is displayed on the CRO, making it possible for a detailed slow examination or a quick review of data. An additional feature is the crosscorrelation statistical plot produced. The cross multiplication trace (of TWODET) is integrated over one frame period (one second). The resultant correlation is stored until the entire 600 frames have been processed. 600 correlation points are plotted with respect to a zero correlation reference. In addition, the mean and standard deviation of each 100 s run segment is computed and plotted (Fig 7). The value of this plot is

REPLAY.VAR

EACH DOT REPRESENTS THE CORRELATION OF ONE SECOND OF DATA



THE MEAN AND STANDARD DEVIATION FOR 600 s OF DATA IS COMPUTED AND DISPLAYED IN 100 s INCREMENTS.

Figure 7 - REPLAY.VAR STATISTICAL PRESENTATION

that it allows for a relative measure of correlation between the EEG signals of interest. Comparison is also made possible between the mean correlations of run segments as well as of different runs. If a broad band pulse (myogram) propagates throughout the cortical area, we can consider the resultant correlation to reflect a slightly higher mean. The pulse will appear at both electrodes and will result in a large positive correlation.

2. REPLAY.CON

Due to the presence of low amplitude extraneous cross multiplication results, it was quite difficult to recognize the occurrence of EEG signal events. We were receiving too much information. REPLAY.CON applies a threshold to the cross multiplication trace. If the trace information is of less amplitude than the threshold, the program zeros that portion. The resultant trace displays only that which is above threshold value. The program also utilizes a running averaging routine. A program parameter specified the number of words desired in the running average of trace 2. For example, if we set the time window (for the number of words) equal to 1 and the threshold equal to 0, the resultant trace 2 would be identical to that of REPLAY.VAR. As with an envelope detector, this program enhances the dominant characteristics of the correlation indication of trace 2. A crosscorrelation plot is provided as in REPLAY.VAR, but is computed from the threshold adjusted cross multiplication results.

3. REPLAY.PLT

This is the program which was utilized to develop the plots presented as "TWODET 70-95 Hz". Single frames

(one s of data) can be easily plotted using this program.

4. REPLAY.CPT

Used primarily for laboratory data examination, this program can plot any number of EEG data frames from a given run. The advantage of this plot is that it allows data examination on a much larger scale than is possible with the CRO display.

B. PROCEDURAL TERMINOLOGY

In order to facilitate the presentation of data, certain terms will imply associated conditions. This list should be used for reference to all runs unless otherwise stated:

1. Run: 600 s of EEG data (a full disk)
2. Run Segment: 100 s of EEG data
3. Slow Clock: 1.5 Hz
4. Fast Clock: 2.8 Hz
5. Scale on all "TWODET 70-95 Hz" plots is identical.
6. Scale on all "REPLAY.VAR" plots is identical.
7. Motor-Premotor: Frontal lobe of the cortex
8. Response Signature: That portion of trace 2 (cross multiplication) which shows relatively large peaks (positive or negative, depending on electrode position) preceded and followed by low amplitude periods. The signature follows a task initiation found on trace 4.
9. Latency: The period from the task initiation to the

beginning of the response signature.

10. Signature Duration: The period from the beginning of the response peak(s) to the end of them. Phase and amplitude characteristics of concurrent tegular activity from traces 1 and 3 were used for this determination.

11. BFB: Biofeedback will be assumed present unless specified to the contrary, ie. "no BFB" or "no visual stimuli".

C. ELECTRODE POSITIONS PRESENTED

We stressed the importance of electrode position for effective EEG signal detection in a task situation. Because of this it was felt that plot presentations of areas other than the motor-premotor area were required. Motor-premotor represents the placement of two primary electrodes close to one another and in the same cortical hemisphere. This was a serial electrode position. One electrode was placed in the premotor area and the other electrode was placed behind the first in the motor area. Fore-and-aft or serial electrode placement resulted in the detection of easily recognized task related response signatures. This was connected to the premotor to motor (fore-and-aft) signal processing flow pattern. Motor-occipital electrodes were placed with the primary electrodes in the same hemisphere but with significant separation. Left motor-right motor presents us with an example of the primary electrodes in different cerebral hemispheres and a large electrode separation. The motor-occipital and left motor-right motor placements will be presented last. It must be emphasized that this is not a chronological presentation. We spent a great deal of time reconfirming the task related preferred frequency of 70-95

Hz. In an effort to locate that portion of the cerebral surface with the greatest occurrence of task related electrical activity, we examined the left motor area, the left occipital area, and the right motor area. The left motor area provided us with the most signal activity which was task related. The motor-occipital and left motor-right motor presentations are a result of the general search. The motor-premotor presentation is a conglomerate of the general search results and later more detailed investigations.

D. LEFT MOTOR TO LEFT PREMOTOR

Accompanying each motor-premotor task segment plot will be an analysis of the entire run segment. This is to provide you with a frame of reference to which the figures may be compared. The statistical presentation is:

* Occurrence of Signature: This is a percentage and is calculated as the ratio of easily recognizable response signatures to the total number of task initiations.

* Latency (mean): The latency times of all of the response signatures were recorded and the mean calculated.

* Latency (S. D.): The standard deviation from the mean was calculated.

* Signature Duration (mean): The duration times of all of the response signatures were recorded and the mean calculated.

* Signature Duration (S. D.): The standard deviation from the mean was calculated.

* Performance (mean): The time that it took for the subject to return the CRO dot to center after each task initiation was recorded and the mean was calculated.

* Performance (S. D.): The standard deviation from the mean was calculated.

1. Baseline

Figure 8 shows the baseline EEG of a subject. The baseline was established with the subject in a relaxed state with no visual stimulation. The screened room, in which the subject sits, was darkened and the CRO was turned off. Note the even distribution of positive and negative correlation indicated on trace 2. Traces 1 and 3 show little similarity in tegular activity.

2. Slow Clock

The tasking peripheral was energized at a clock rate of 1.5 Hz, and the subject began the task series.

a. Normal Stick Control

Figure 9 shows the cortical response to the task. BFB was utilized in this run segment. Trace 2 shows the response signature occurring 0.31 s after task initiation. The response signature appears to last for about 0.23 s and then a decrease in tegular amplitude as well as a loss in the phase relationship occurs. There is a relatively low amplitude period before and after the peaking action occurs on trace 2. The subject felt that he had done a good job during this run segment. Analysis of the run segment revealed the following:

* Occurrence of signature: 76%

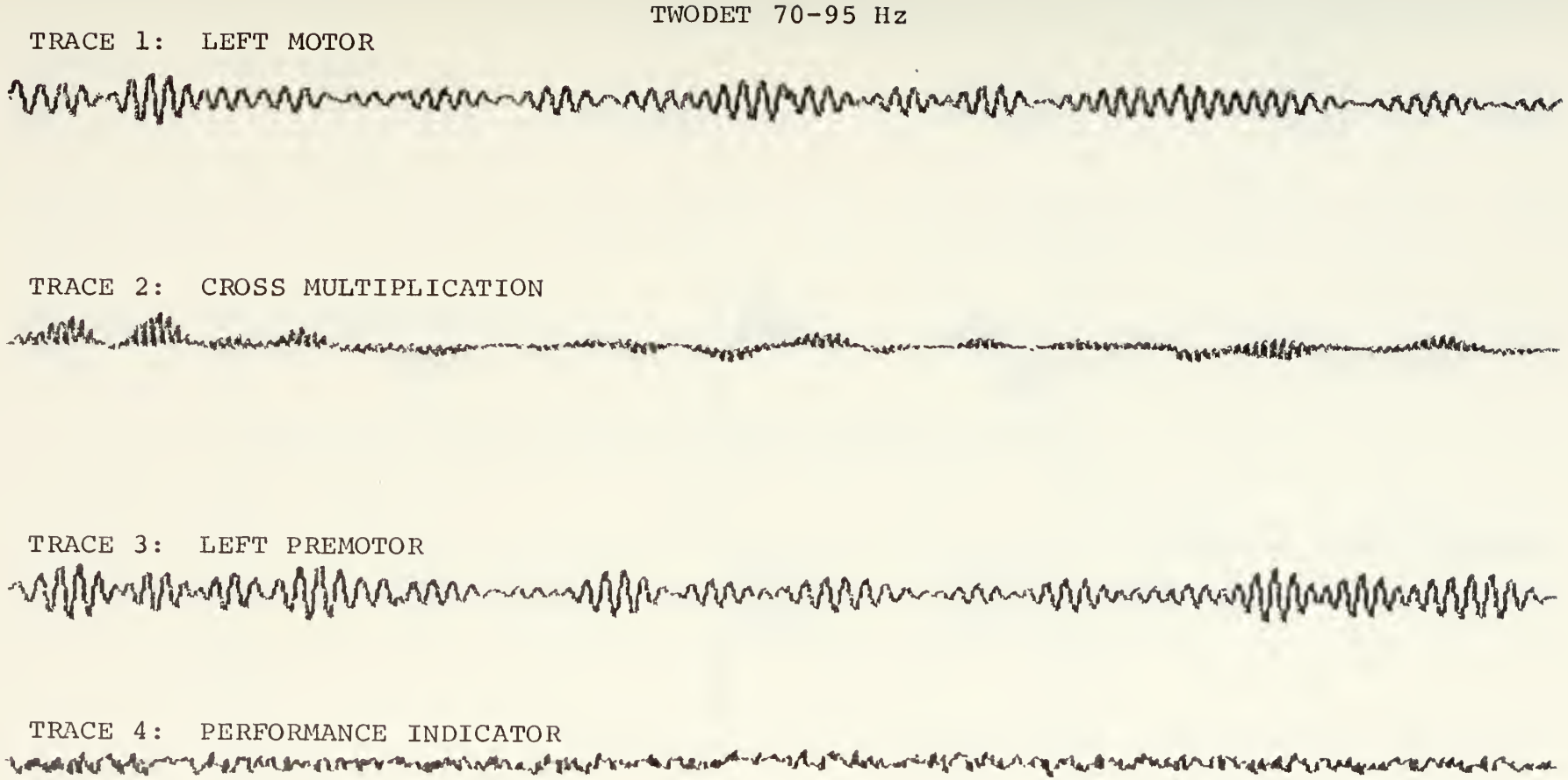


Figure 8 - MOTOR-PREMOTOR, RELAXED

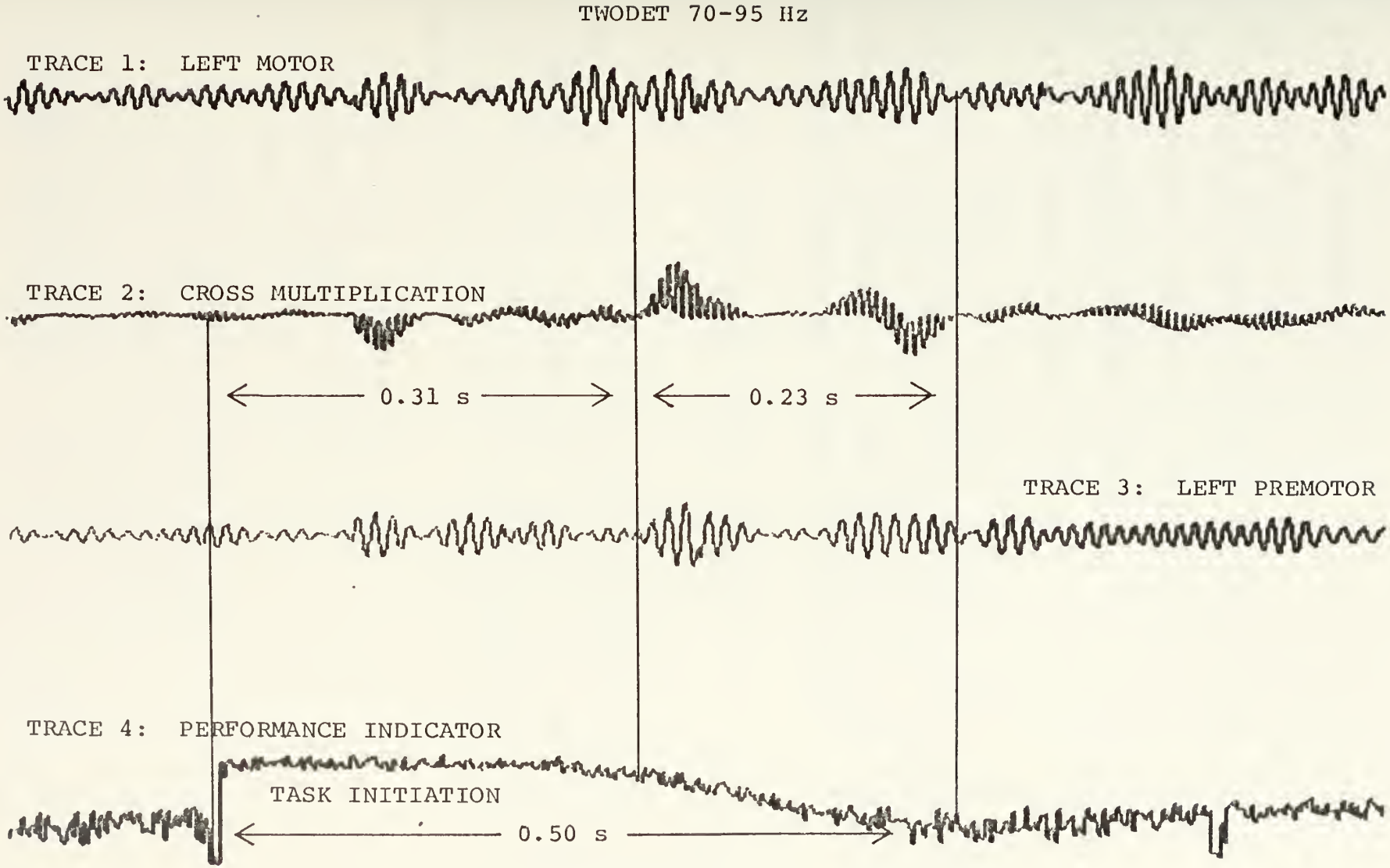


Figure 9 - MOTOR-PREMOTOR, SLOW CLOCK

* Latency (mean): 0.19 s

* Latency (S. D.): 0.10 s

* Signature Duration (mean): 0.13 s

* Signature Duration (S. D.): 0.04 s

* Performance (mean): 0.55 s

* Performance (S. D.): 0.14 s

Figure 9 is fairly typical of the run. Reference to figures 16 through 25 might be of interest as we review individual plots. Those figures represent the statistical analysis of 1800 seconds of EEG data from the same subject taken over a period of three weeks.

b. Normal Stick Control, No BFB

The only change from the last run was the removal of BFB. Figure 10 shows a decrease in the time to the response signature compared to Fig 9. The response signature lasts for a longer period. The subject once again reported that he did a good job. Analysis of this run segment revealed:

* Occurrence of Signature: 46%

* Latency (mean): 0.14 s

* Latency (S. D.): 0.07 s

* Signature Duration (mean): 0.11 s

* Signature Duration (S. D.): 0.04 s

* Performance (mean): 0.50 s

* Performance (S. D.): 0.11 s

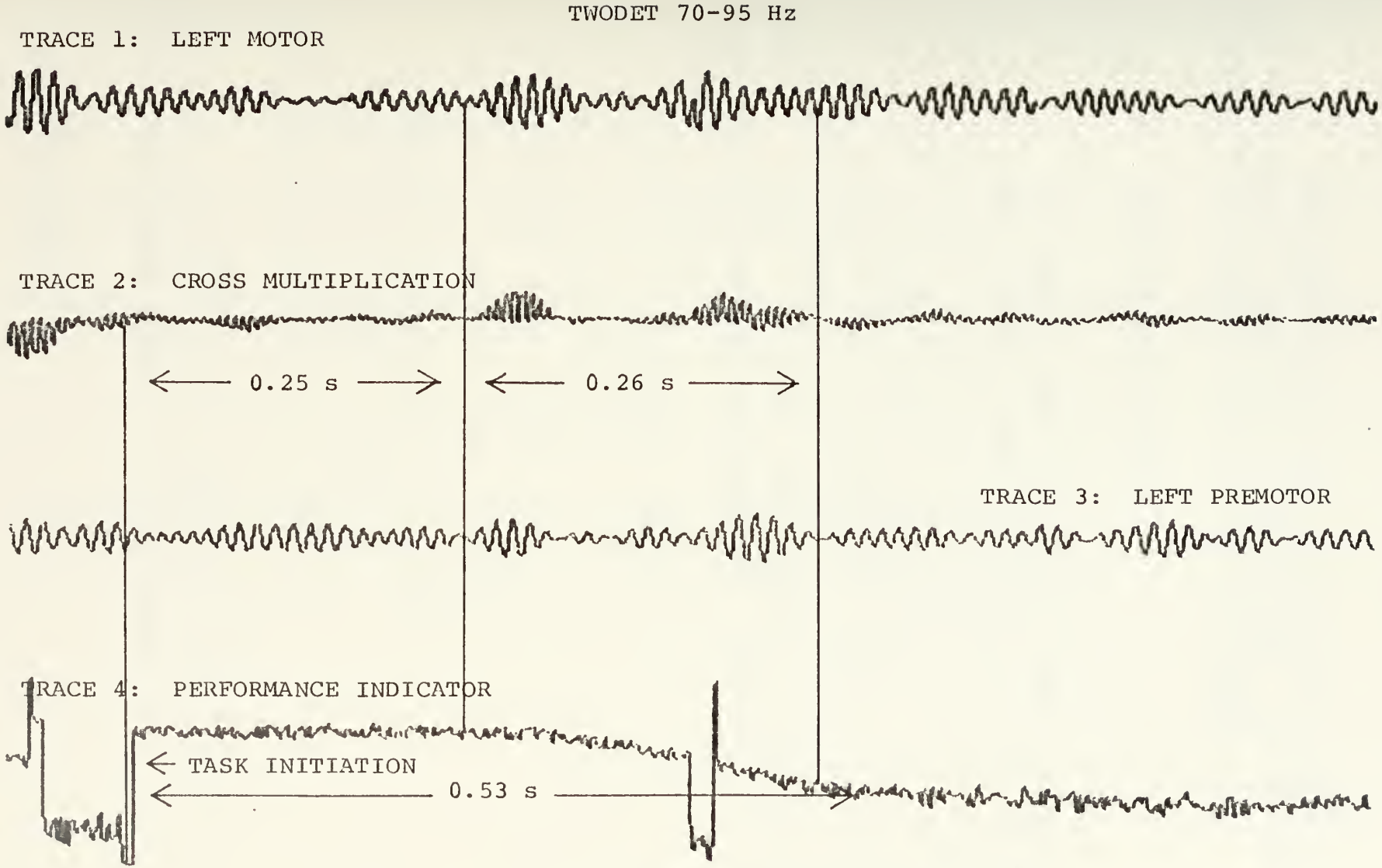


Figure 10 - MOTOR-PREMOTOR, SLOW CLOCK, NO BFB

For some reason, there was quite a decrease in the occurrence of signature without the BFB. The subject's performance did improve over the last run segment.

c. Reversed Stick Control

The subject never felt that he could accomplish the task with reversed controls as well as he could with normal stick control. That was his evaluation over a three month period and a total of 30 runs that he made. This is pointed out to emphasize that reversed control was by far the most difficult task. It required a complete alteration in the task perception and control on the part of the subject. Figure 11 shows that there is, once again, an easily identifiable response signature. Analysis of this run segment showed:

* Occurrence of Signature: 83%
* Latency (mean): 0.18 s
* Latency (S. D.): 0.11 s
* Signature Duration (mean): 0.12 s
* Signature Duration (S. D.): 0.04 s
* Performance (mean): 0.95 s
* Performance (S. D.): 0.19 s

The plot is quite typical of the run segment, as seen from the values above. This was by far the worst subject performance of any of the run segments.

3. Fast Clock

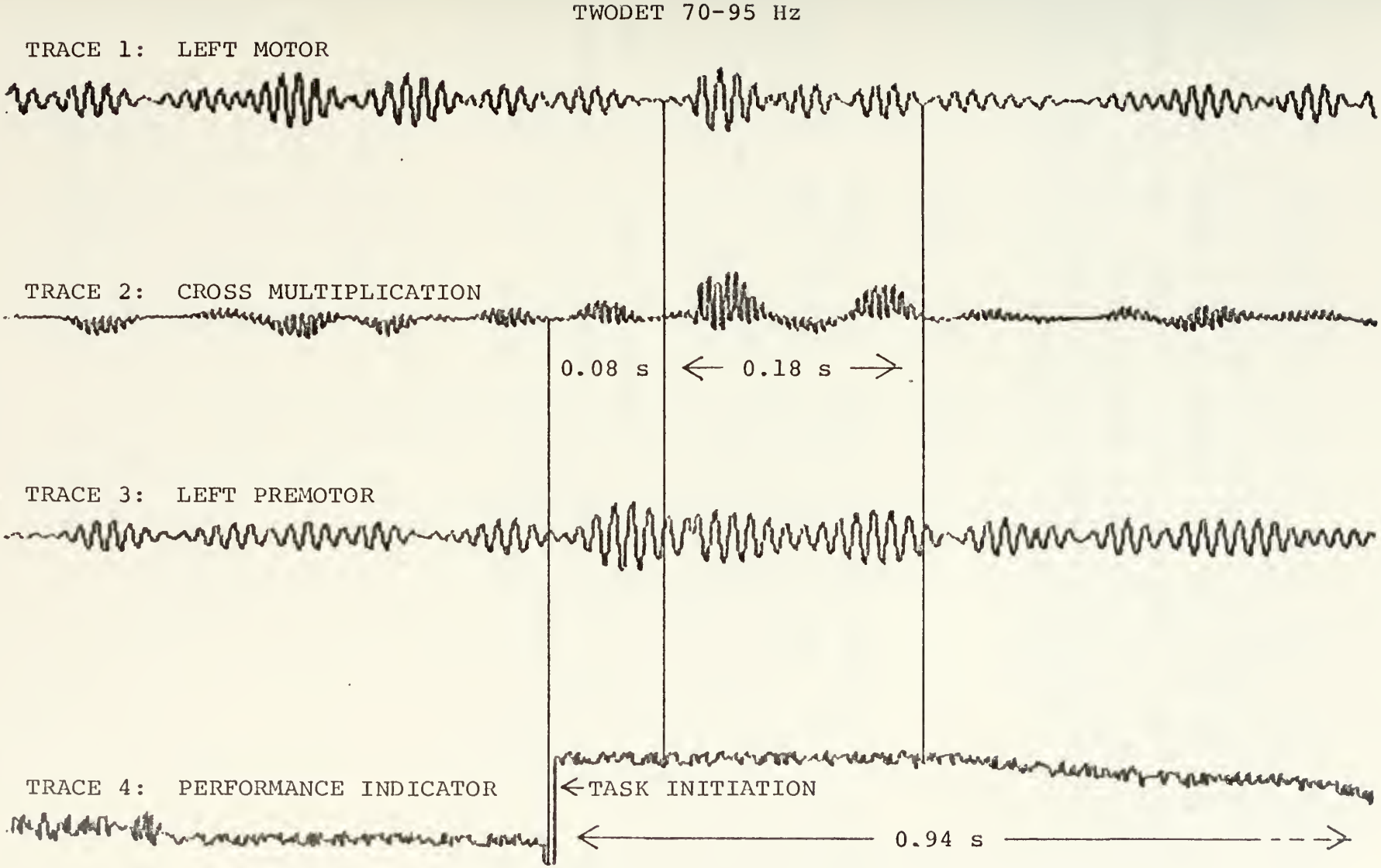


Figure 11 - MOTOR-PREMOTOR, SLOW CLOCK, REVERSED CONTROL

We increased the clock rate of the tasking peripheral to 2.8 Hz for these last two runs. At this clock rate, the subject is almost constantly controlling the CRO dot. The resultant profusion of task related responses makes signature analysis quite difficult. Run segments using a fast clocking were reported by the subject to be more difficult than those run segments with a slow clock but less difficult than those with reversed control.

a. Normal Stick Control

Figure 12 shows the now familiar response signature. The latency is only 0.06 s and the signature duration 0.18 s. The subject reported that he felt greater accomplishment during this segment than in earlier segments. The subject consistently felt better with BFB than without. This feeling persisted throughout the entire three months of runs. For reasons unknown, the fast clock with BFB run segment caused more subject comment on BFB than the other two segments with BFB. The subject commented that the BFB may have had a relaxing effect on him. Run segment analysis:

* Occurrence of Signature: 72%
* Latency (mean): 0.13 s
* Latency (S. D.): 0.07 s
* Signature Duration (mean): 0.13 s
* Signature Duration (S. D.): 0.04 s
* Performance (mean): 0.53 s
* Performance (S. D.): 0.12 s

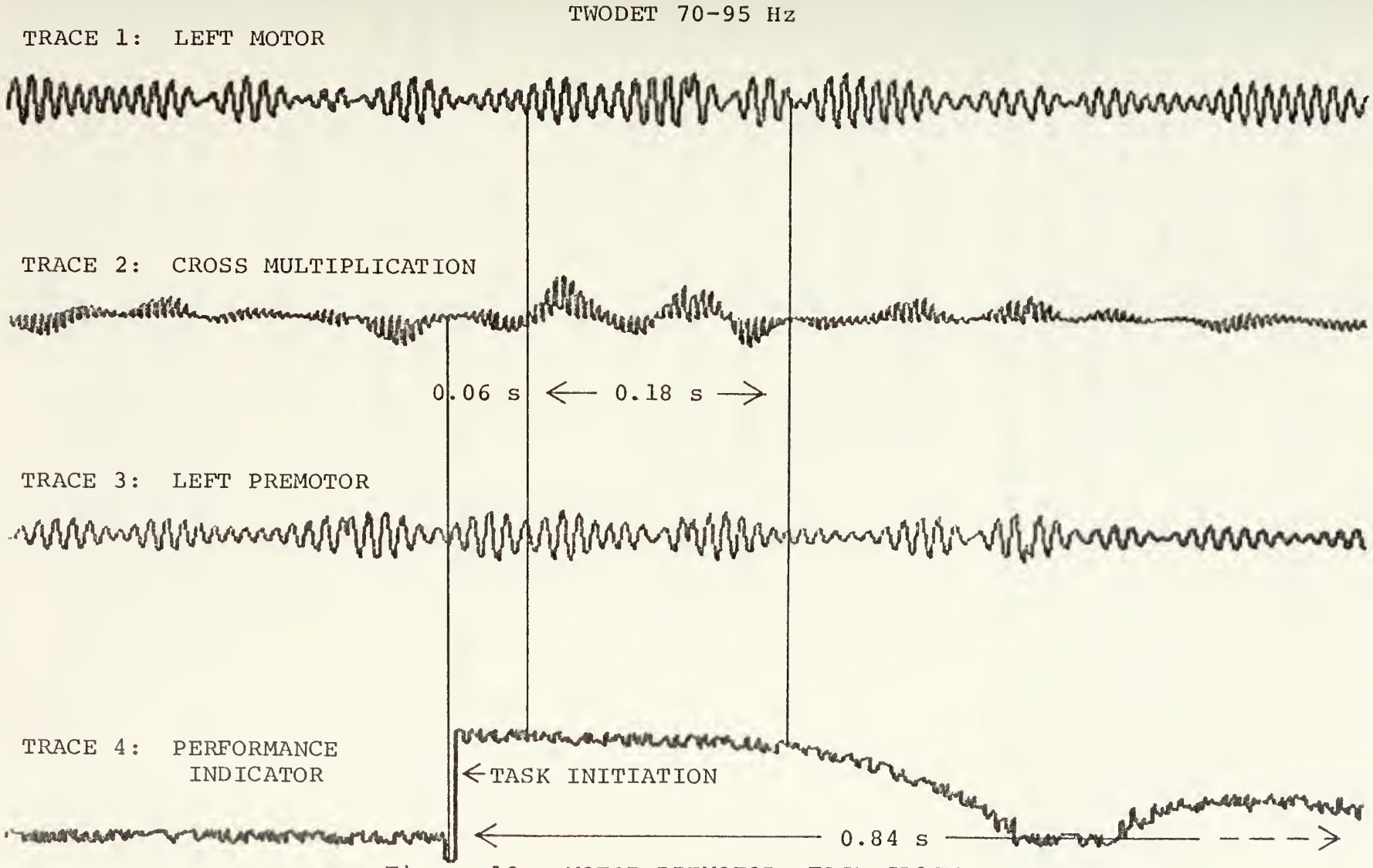


Figure 12 - MOTOR-PREMOTOR, FAST CLOCK

b. Normal Stick Control, No BFB

Notice that the performance in this plot is much better than in any other plots or data analysis presented so far (Fig 13). The subject reported that he felt a tremendous sense of accomplishment from this run segment. At the end of the research, he referred to this run segment as the best of all 30 runs included in the research. Data analysis:

* Occurrence of Signature: 57%
* Latency (mean): 0.16 s
* Latency (S. D.): 0.06 s
* Signature Duration (mean): 0.17 s
* Signature Duration (S. D.): 0.06 s
* Performance (mean): 0.51 s
* Performance (S. D.): 0.14 s

The performance, contrary to the subject's belief, was not the "super run" that he thought. The run segment with a slow clock, normal stick control, and no BFB had slightly better performance times.

4. Crosscorrelation

With the electrodes located in the motor-premotor area, one would expect a certain amount of positive correlation between the signals detected. Figure 14 shows that this was the case. Recall that the primary electrodes were only 2.4 cm apart.

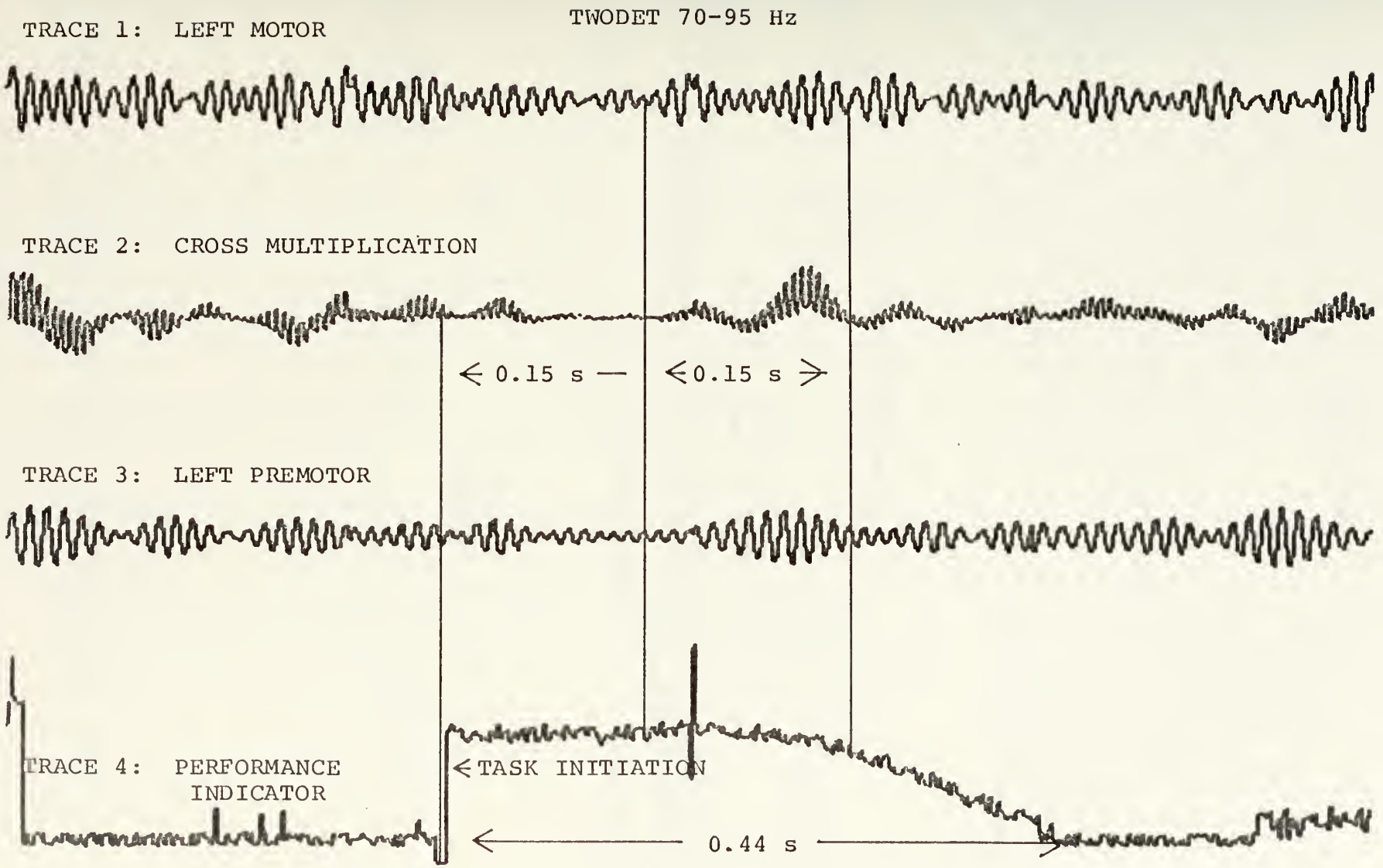


Figure 13 - MOTOR-PREMOTOR, FAST CLOCK, NO BFB

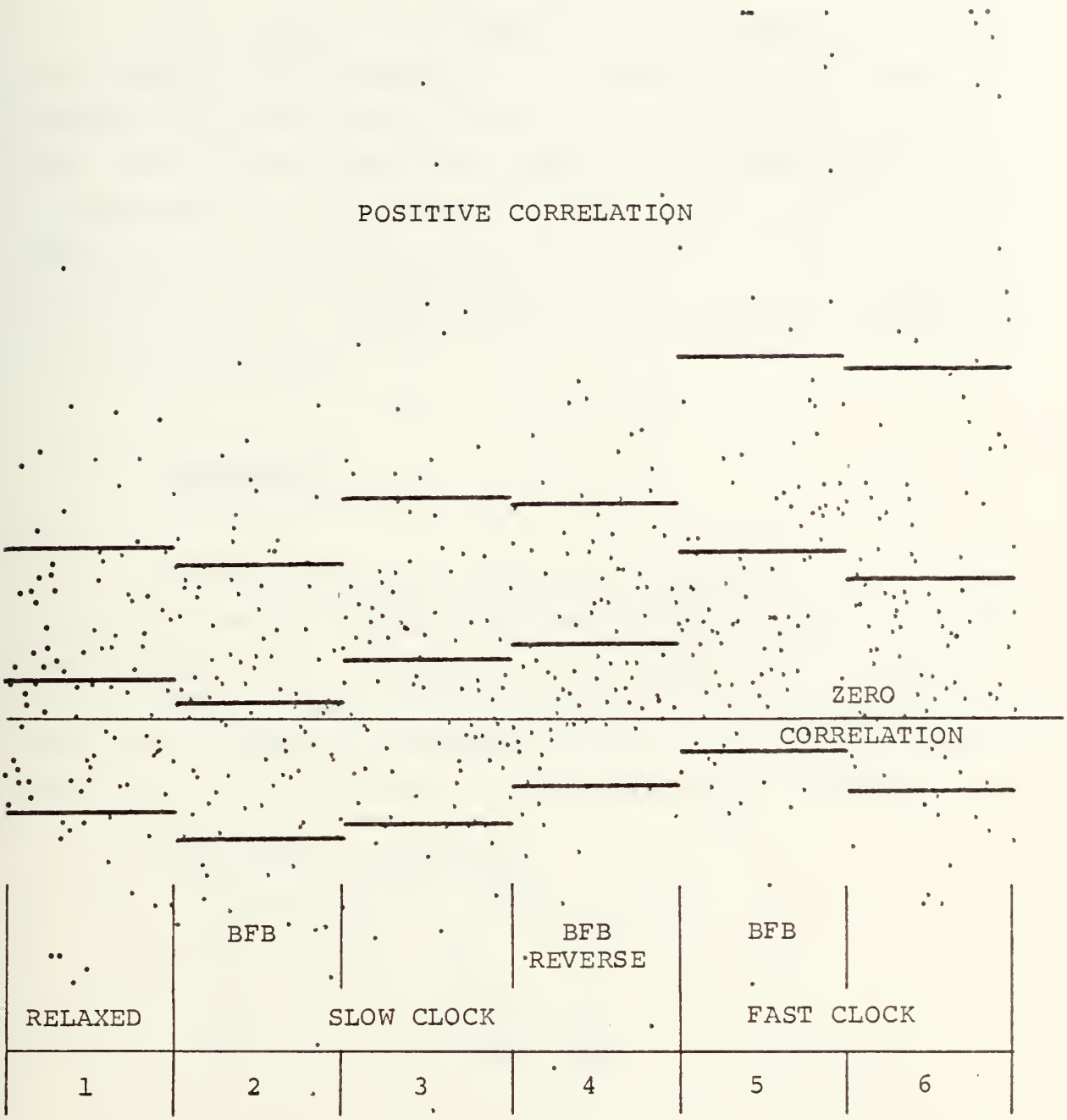


Figure 14 - CROSSCORRELATION OF LEFT MOTOR AND PREMOTOR

This plot is similar to those of other motor-premotor runs except for the mean of the fifth run segment which was usually found below that of the sixth and above that of the fourth run segment. This abnormality can be explained by the presence of some myogram activity in run segment five. Although not to be associated with this run presentation, Fig 15 is a typical plot of a motor-premotor run (also Fig 7). Observe the relative position of the mean of run segment five.

5. Conclusions

We have seen data plots and subsequent calculations extracted from one run. The same calculations are now represented as a basis for comparative analysis. Conclusions were not, however, drawn from the evidence of one run. Graphical presentation of statistical information from three motor-premotor runs are also made available.

* Occurrence of Signature:
    - Reversed Stick Control: 83%
    - Slow Clock: 76%
    - Fast Clock: 72%
    - Fast Clock, No BFB: 57%
    - Slow Clock, No BFB: 46%

Since we are interested in the development of more sophisticated methods for response signature statistical analysis, it is reasonable to specify those parameters which, when varied, will optimize the occurrence of the task related response signature. All three of the primary electrode positions discussed provided

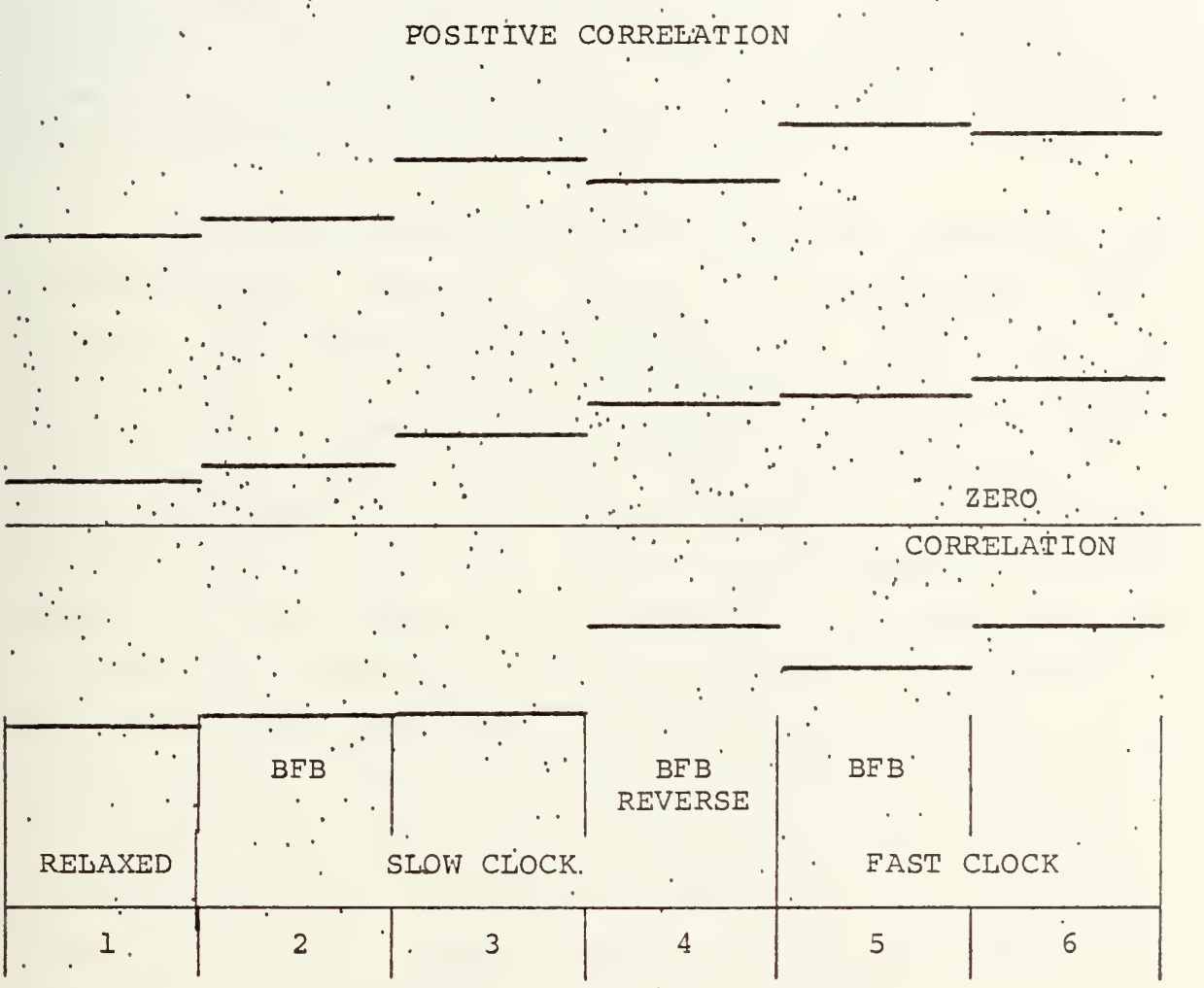


Figure 15 - TYPICAL MOTOR-PREMOTOR CROSSCORRELATION

a 62-64% average occurrence of signature. It has been demonstrated that the task related preferred frequency range is 70-95 Hz [Ref. 7]. We can now elaborate this by concluding that the more difficult the task (reversed stick control in this research), the greater becomes the occurrence of the response signature. For all of the motor-premotor runs, the reversed stick control produced signatures 77% of the time (Fig 16). Also shown is a 73% occurrence of signature for all runs conducted, including motor-occipital and left motor-right motor.

We have determined that the response signature has characteristics directly related to the skilled motor function. Are these characteristics task related or are they peculiar to a given individual? If the response signature is a trademark which varies from person to person, what impact does training have on the signature characteristics? Let us first examine the latency characteristic (the time from task initiation to the beginning of the signature). Figures 18, 19, and 20 show the means and standard deviations of latency with respect to the various task segments. One conclusion to be drawn from this is that, while the mean may vary slightly from task to task, latency is relatively constant for this individual. If we can say that reversed stick control is an unusually difficult task when compared with the others, and therefore ignore it for a second, another interesting possibility presents itself. It appears that the latency is shorter with BFB introduced. First compare the slow clock segments, then compare the fast clock segments. If the reversed stick control segment is compared with the fast clock segments and the slow clock segments, it can be seen that the latency is longer with a more difficult task.

* Latency (mean):
    - Slow Clock, No BFB: 0.14 s

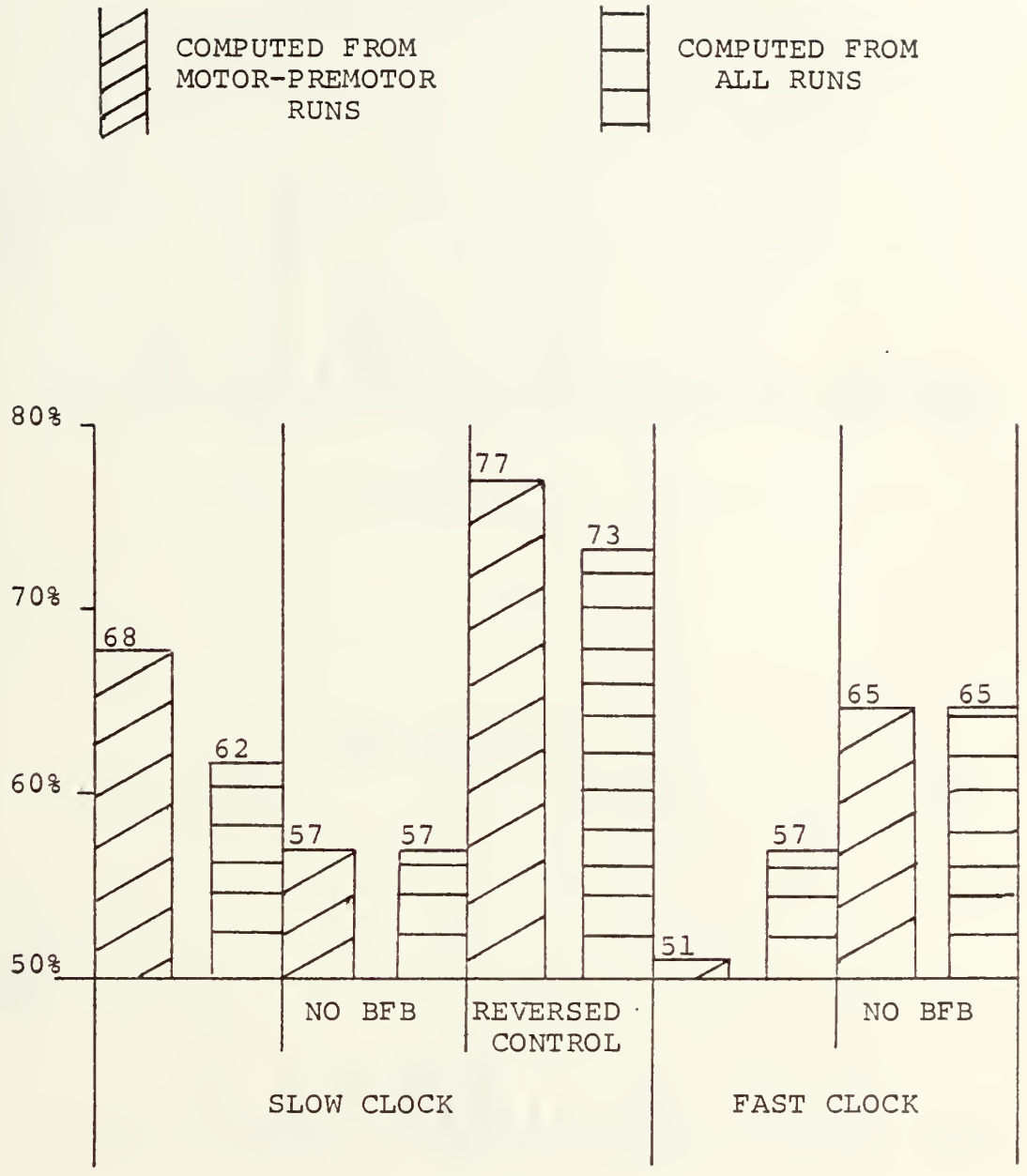
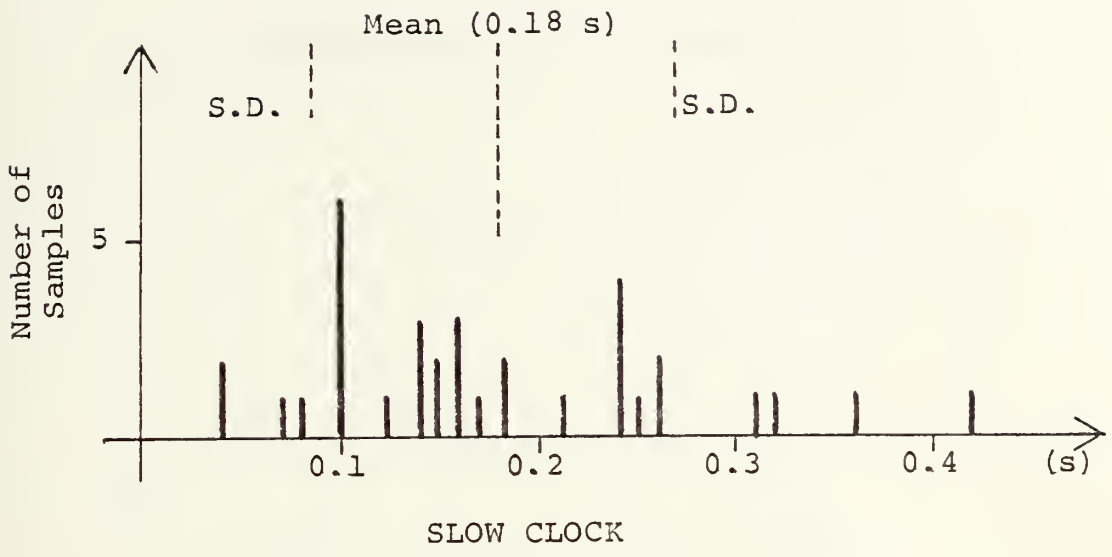
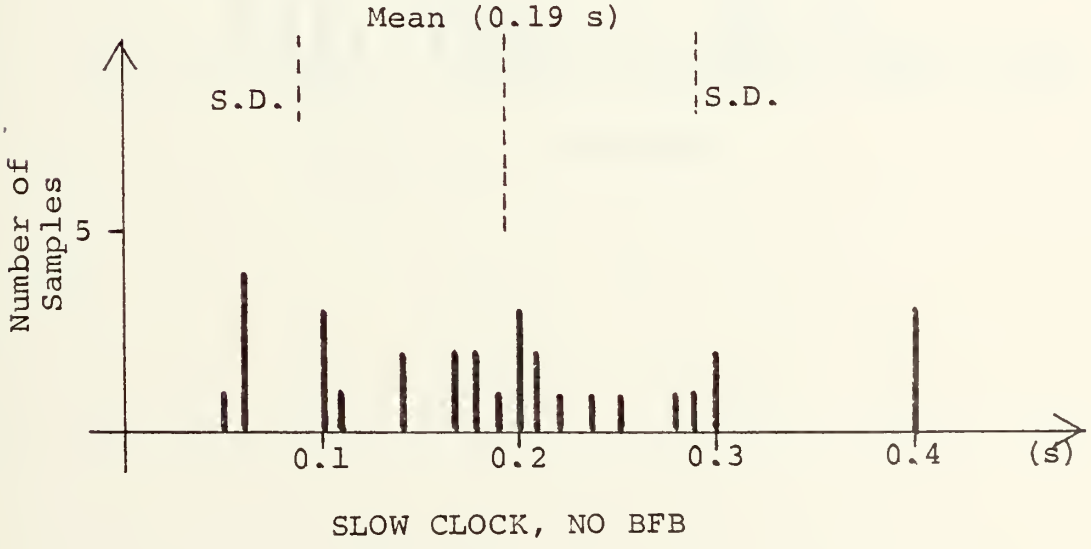


Figure 16 - RESPONSE SIGNATURE OCCURRENCE

LEFT MOTOR TO LEFT PREMOTOR



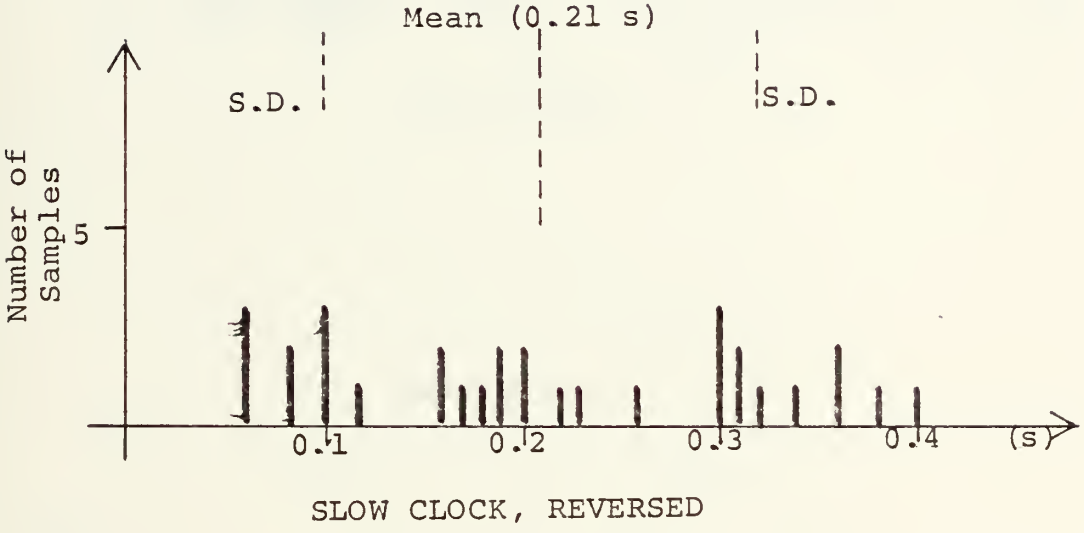
SLOW CLOCK



SLOW CLOCK, NO BFB

Figure 17 - SUMMARY OF LATENCY

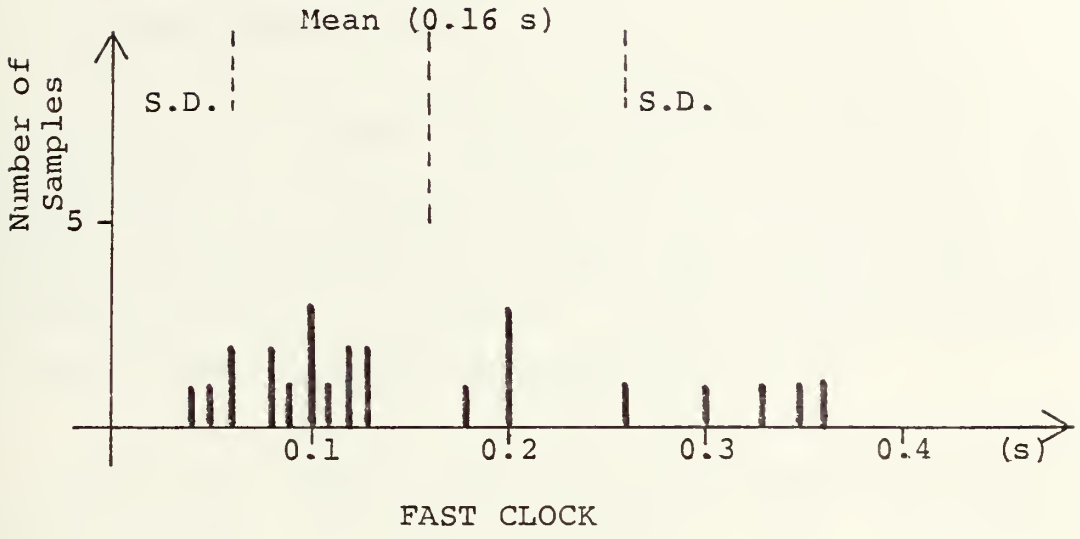
LEFT MOTOR TO LEFT PREMOTOR



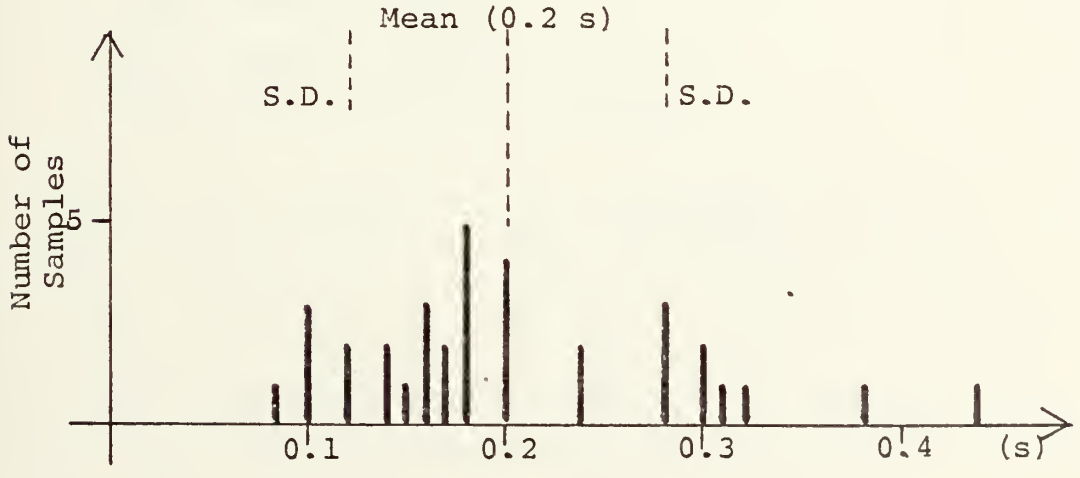
SLOW CLOCK, REVERSED

Figure 18 - SUMMARY OF LATENCY

LEFT MOTOR TO LEFT PREMOTOR



FAST CLOCK



FAST CLOCK, NO BFB

Figure 19 - SUMMARY OF LATENCY

- Fast Clock, No BFB: 0.16 s
- Reversed Stick Control: 0.18 s
- Fast Clock: 0.18 s
- Slow Clock: 0.19 s

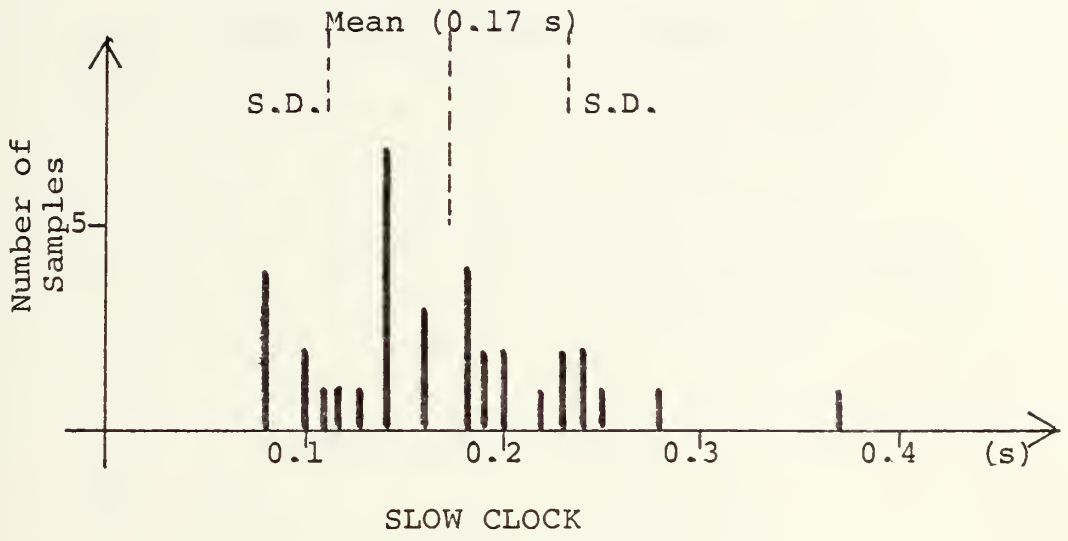
This is a comparative tabulation of the data presented earlier which accompanied the EEG plots. When individual runs, such as this one, are studied and then compared with the results from other runs, we can make only one conclusion about the latency: it is relatively constant from task to task, lasting approximately 0.18 s.

The other response signature characteristic which we examined was the signature duration. From the earlier motor-premotor data presentation:

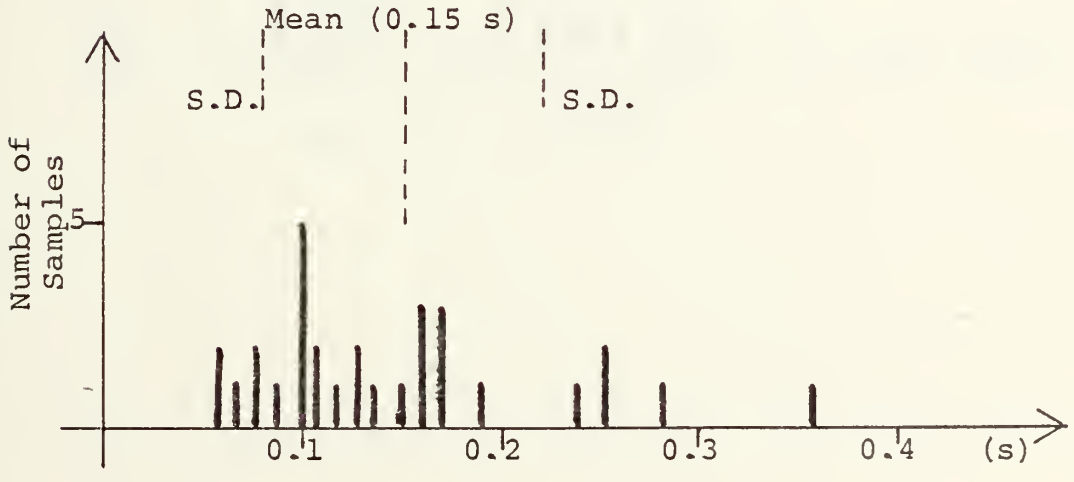
* Signature Duration (mean):
  - Slow Clock, No BFB: 0.11 s
  - Reversed Stick Control: 0.12 s
  - Fast Clock: 0.13 s
  - Slow Clock: 0.13 s
  - Fast Clock, No BFB: 0.17 s

There is nothing in this comparison which can lead us to any conclusion. If, however, we study the results of three runs, as seen in figures 20, 21, and 22, it becomes apparent that the signature duration mean is almost a constant 0.17 s. As you know, we can get a measure of the individual's performance from trace 4 of the TWODET data. We found that this gave us a sound statistical measure of the subject's improvement in task accomplishment over a period of time. This subject improved markedly from the run presented, whose data we have been reviewing, to his last run. This was an expected trend. The more he performed the tasking sequence, the better he became. From his last and best task run, we found the following results:

LEFT MOTOR TO LEFT PREMOTOR



SLOW CLOCK



SLOW CLOCK, NO BFB

Figure 20 - SUMMARY OF SIGNATURE DURATION

LEFT MOTOR TO LEFT PREMOTOR

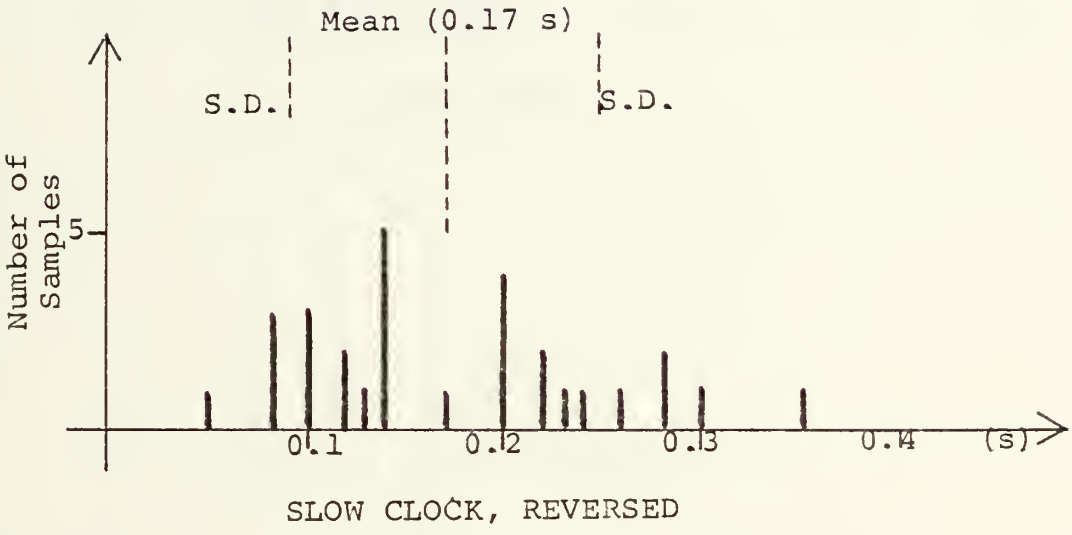
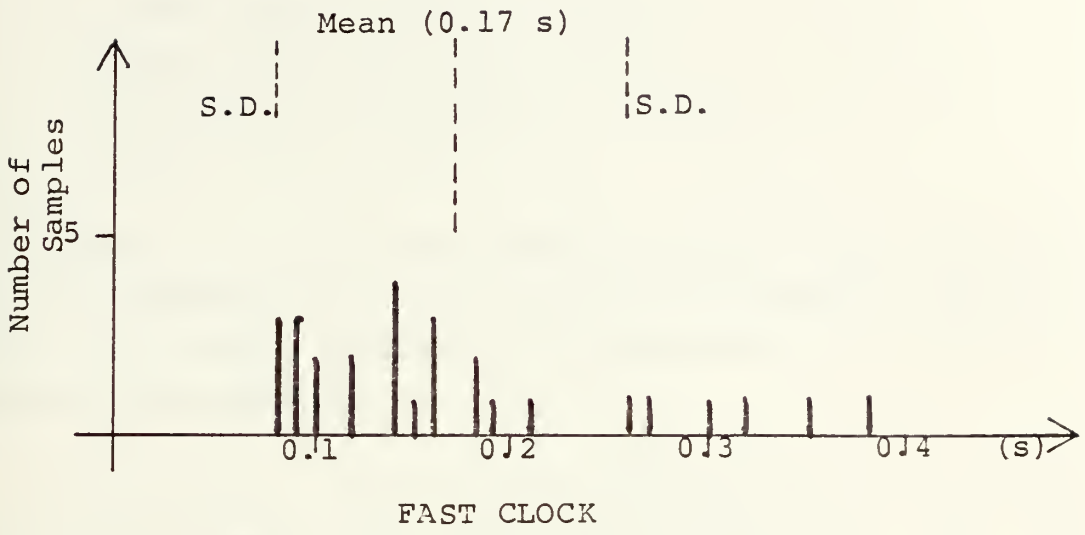
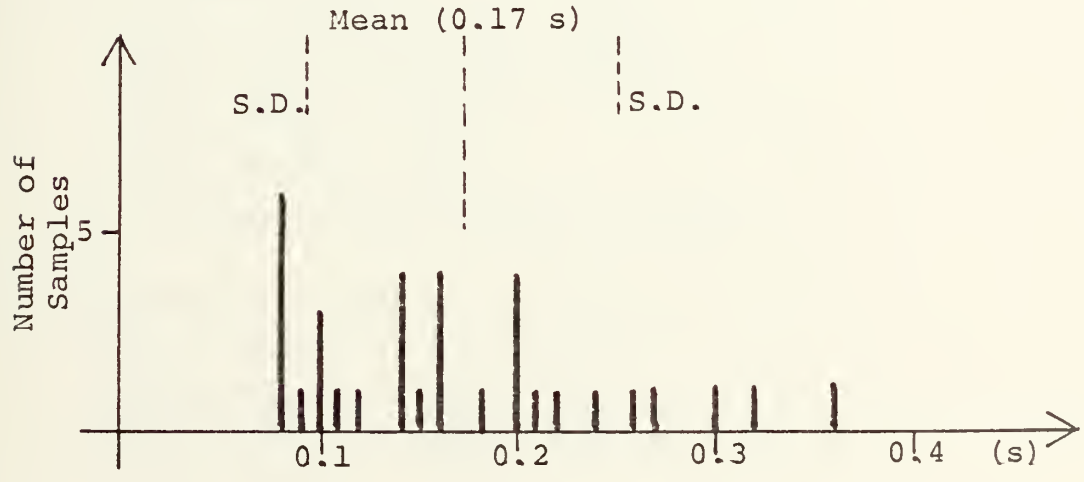


Figure 21 - SUMMARY OF SIGNATURE DURATION

LEFT MOTOR TO LEFT PREMOTOR



FAST CLOCK



FAST CLOCK, NO BFB

Figure 22 - SUMMARY OF SIGNATURE DURATION

* Signature Duration (mean):
    - Slow Clock: 0.17 s
    - Fast Clock, No BFB: 0.17 s
    - Slow Clock, No BFB: 0.17 s
    - Reversed Stick Control: 0.19 s
    - Fast Clock: 0.20 s

Notice how the duration period has increased over that of the earlier run. The correlation between a person's ability to perform a task and his signature duration is an interesting possibility.

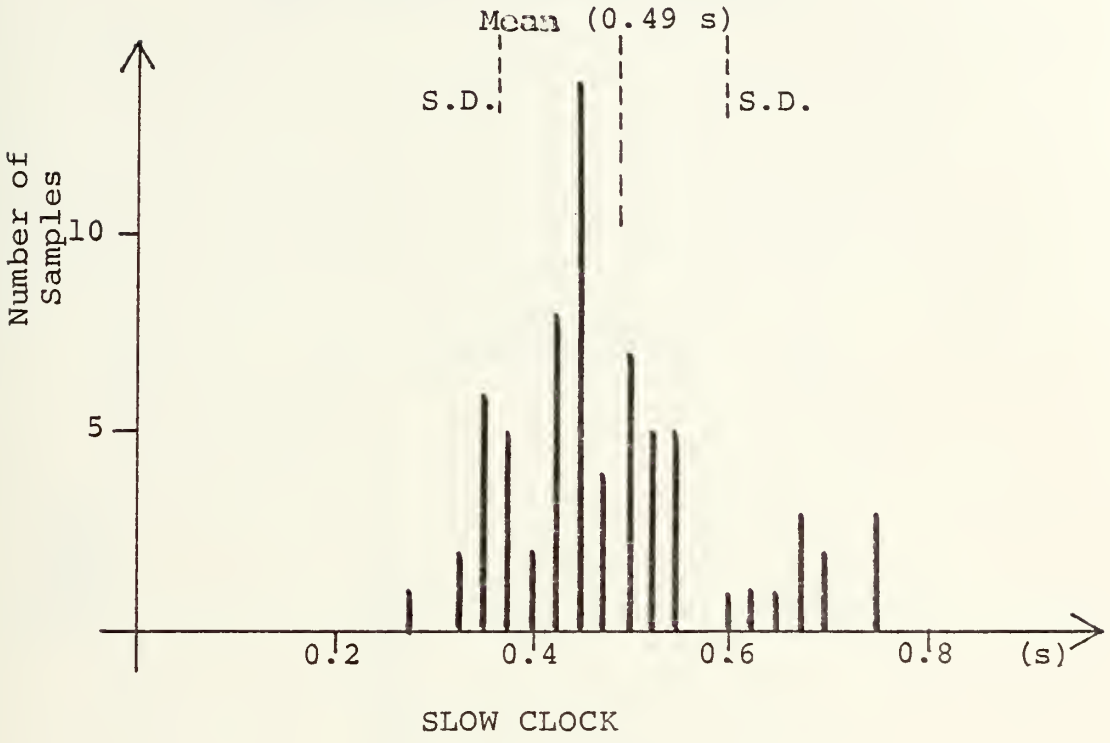
The next two sets of data are presented to show the subject's improvement over the last seven days of EEG runs on him. The first set was taken from the earlier motor-premotor analysis of this section. The second data set comes from his last run.

* Performance (mean):
    - Slow Clock, No BFB: 0.50 s
    - Fast Clock, No BFB: 0.51 s
    - Fast Clock: 0.53 s
    - Slow Clock: 0.55 s
    - Reversed Stick Control: 0.95 s

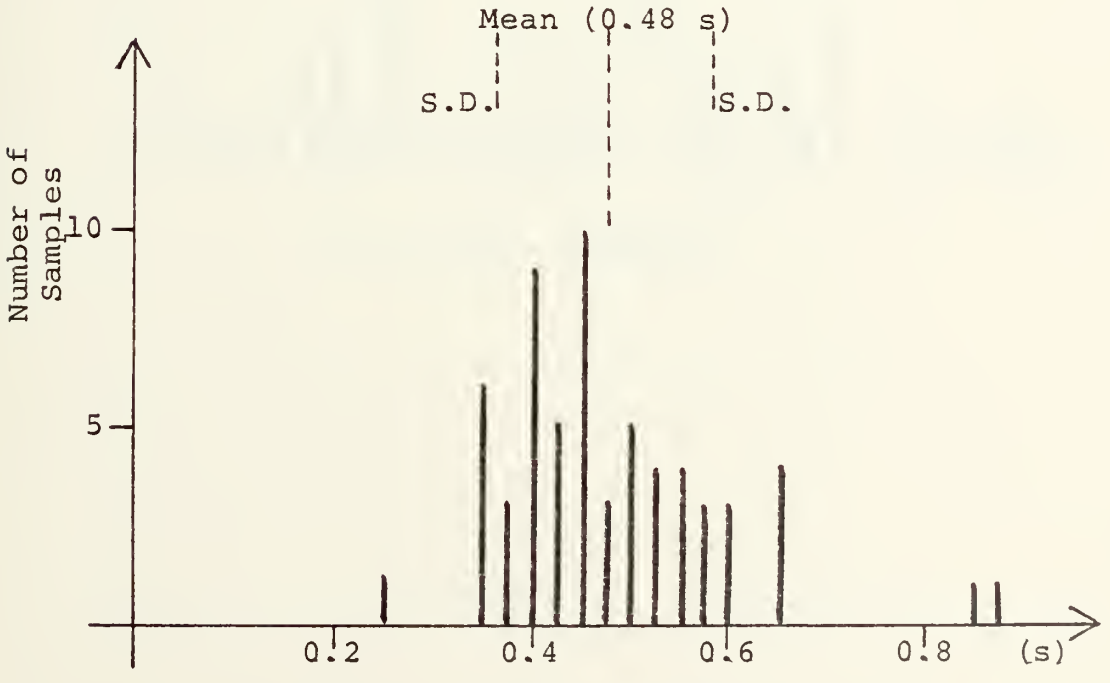
* Performance (mean):
    - Fast Clock, No BFB: 0.44 s
    - Slow Clock: 0.45 s
    - Slow Clock, No BFB: 0.47 s
    - Fast Clock: 0.47 s
    - Reversed Stick Control: 0.55 s

Figures 23, 24, and 25 present an overall performance indication related to the task sequences. From the graphical presentation as well as from the subject's own evaluation of his performance we can draw the following

LEFT MOTOR TO LEFT PREMOTOR



SLOW CLOCK



SLOW CLOCK, NO BFB

Figure 23 - PERFORMANCE INDICATION

LEFT MOTOR TO LEFT PREMOTOR

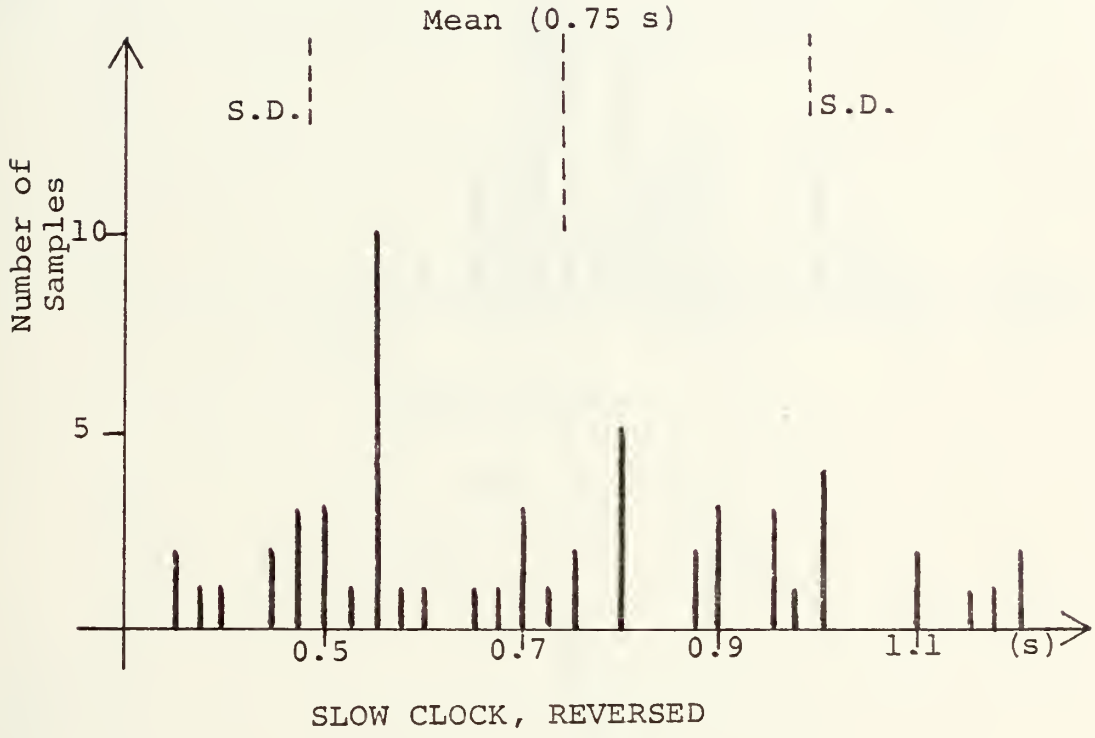
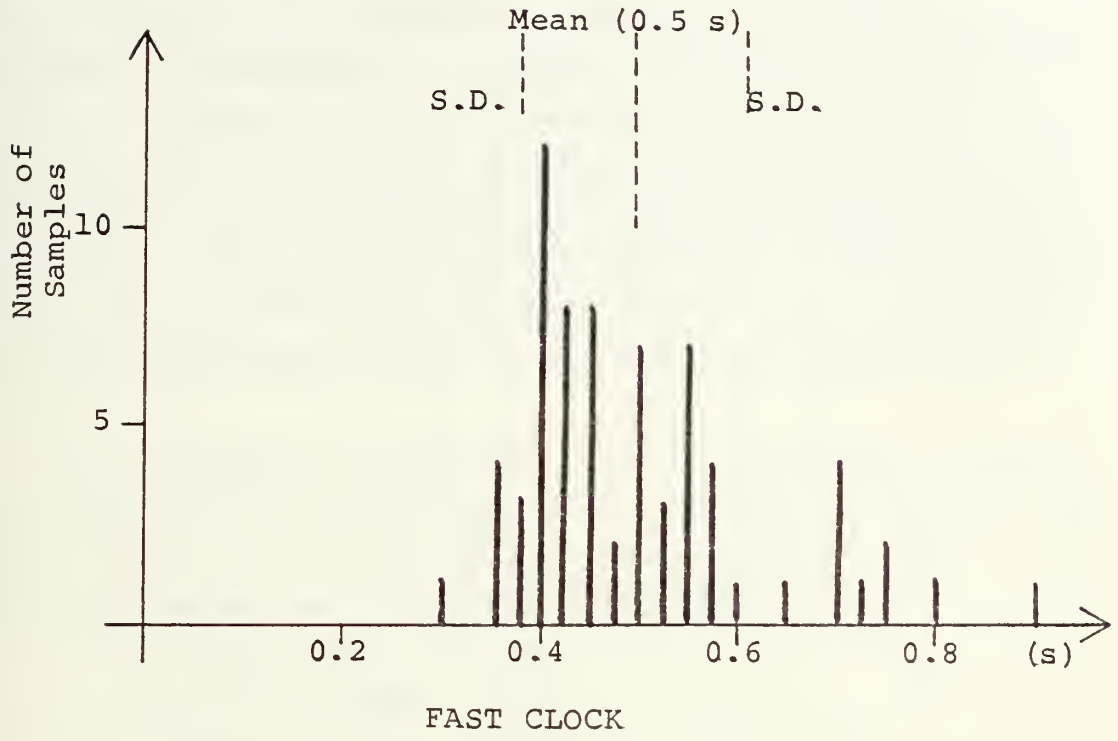
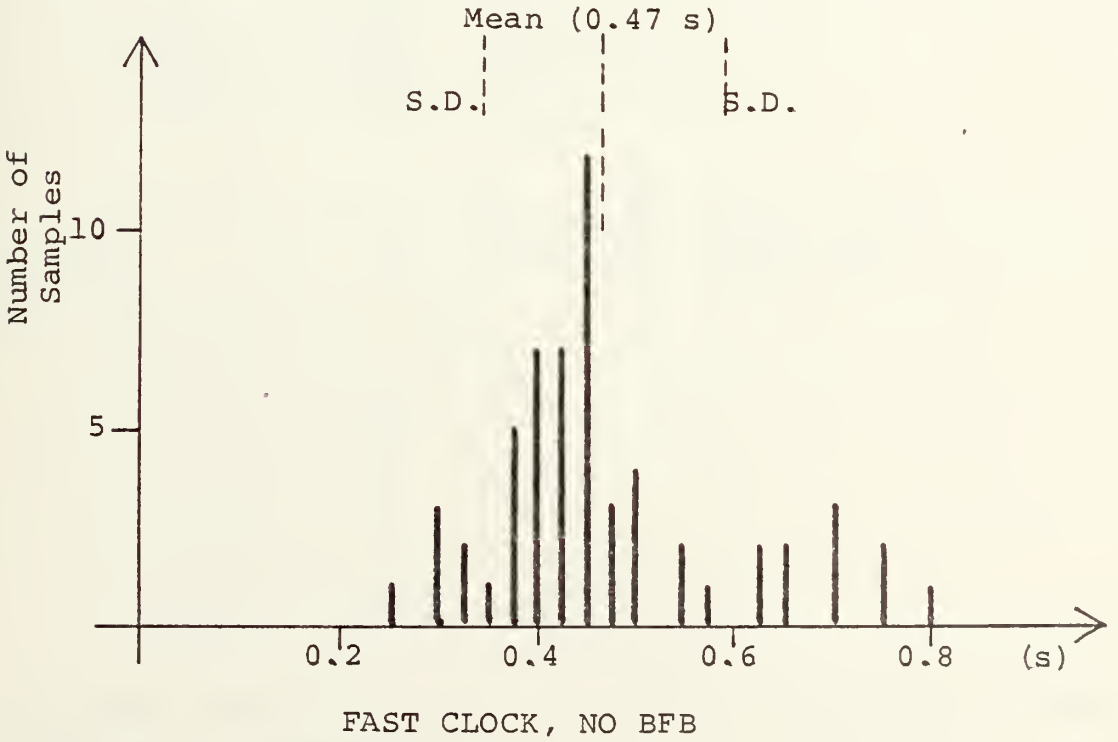


Figure 24 - PERFORMANCE INDICATION

LEFT MOTOR TO LEFT PREMOTOR



FAST CLOCK



FAST CLOCK, NO BFB

Figure 25 - PERFORMANCE INDICATION

conclusions. BFB does in fact impact on the subject's ability to perform. The subject consistently reported that he missed the BFB when it was removed. This same effect was true with two other subjects during the course of the research. The subject also reported that BFB had a soothing or relaxing effect on him. Throughout the analysis of run data, we have found that there is an apparent decrease in the subject's performance when accompanied by BFB. Due to the rather short task segment duration (100 s), it was decided that a longer task segment (10 min) was required to verify the influence of BFB on the subject's performance.

We conducted two special runs. The first run was 10 min long without interruption. The tasking peripheral clock was set at 2.0 Hz and the subject was provided BFB. Data analysis revealed the following performance times:

- Frames 0-100: 0.42 s
- Frames 101-200: 0.46 s
- Frames 201-300: 0.47 s
- Frames 301-400: 0.46 s
- Frames 401-500: 0.48 s
- Frames 501-600: 0.44 s

The second run was also conducted for 10 min without interruption. The only difference being that we did not provide the subject with BFB.

- Frames 0-100: 0.39 s
- Frames 101-200: 0.39 s
- Frames 201-300: 0.39 s
- Frames 301-400: 0.42 s
- Frames 401-500: 0.39 s
- Frames 501-600: 0.42 s

This seems to indicate that the subject performed the task better <u>without</u> BFB.

E. LEFT MOTOR TO LEFT OCCIPITAL

Prior to the run, the electrode placement was checked by observing the cross multiplication trace of the left motor to left premotor signals. This check provided us with a certain degree of confidence in the system as well as the subject. Having established our standard, we shifted to the primary pick up electrodes. There was no electrode relocation. The electrode leads were simply plugged into appropriate amplifier channels for the left motor to left occipital run.

1. Baseline

The baseline was collected with the subject in a relaxed state within the screened room. The lights were out and the tasking peripheral CRO was turned off. Figure 26 shows one second of the run segment. Trace 1 has tegules of about the same duration and amplitude of trace 3. The occipital seemed to be a bit more erratic than the motor area. The cross multiplication trace gave us some indication that we might expect a more negatively oriented correlation than we found with the motor-premotor data. The arbitrary peaks and valleys of the cross multiplication trace indicated that this was a good reference run segment.

2. Slow Clock

a. Normal Stick Control

The response signatures were unlike those of the motor-premotor (Fig 27). We could not be certain that what

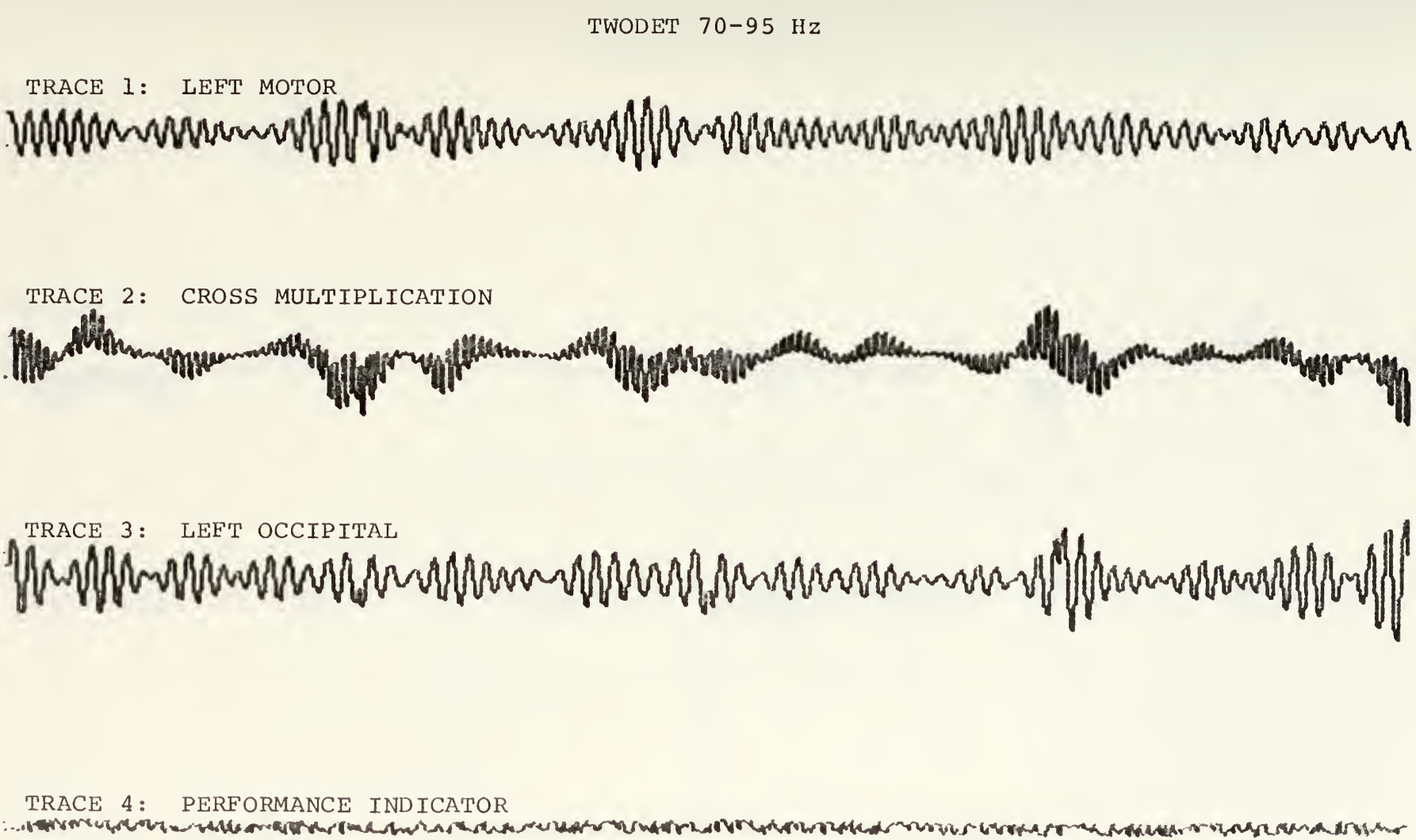


Figure 26 - MOTOR-OCCIPITAL, RELAXED

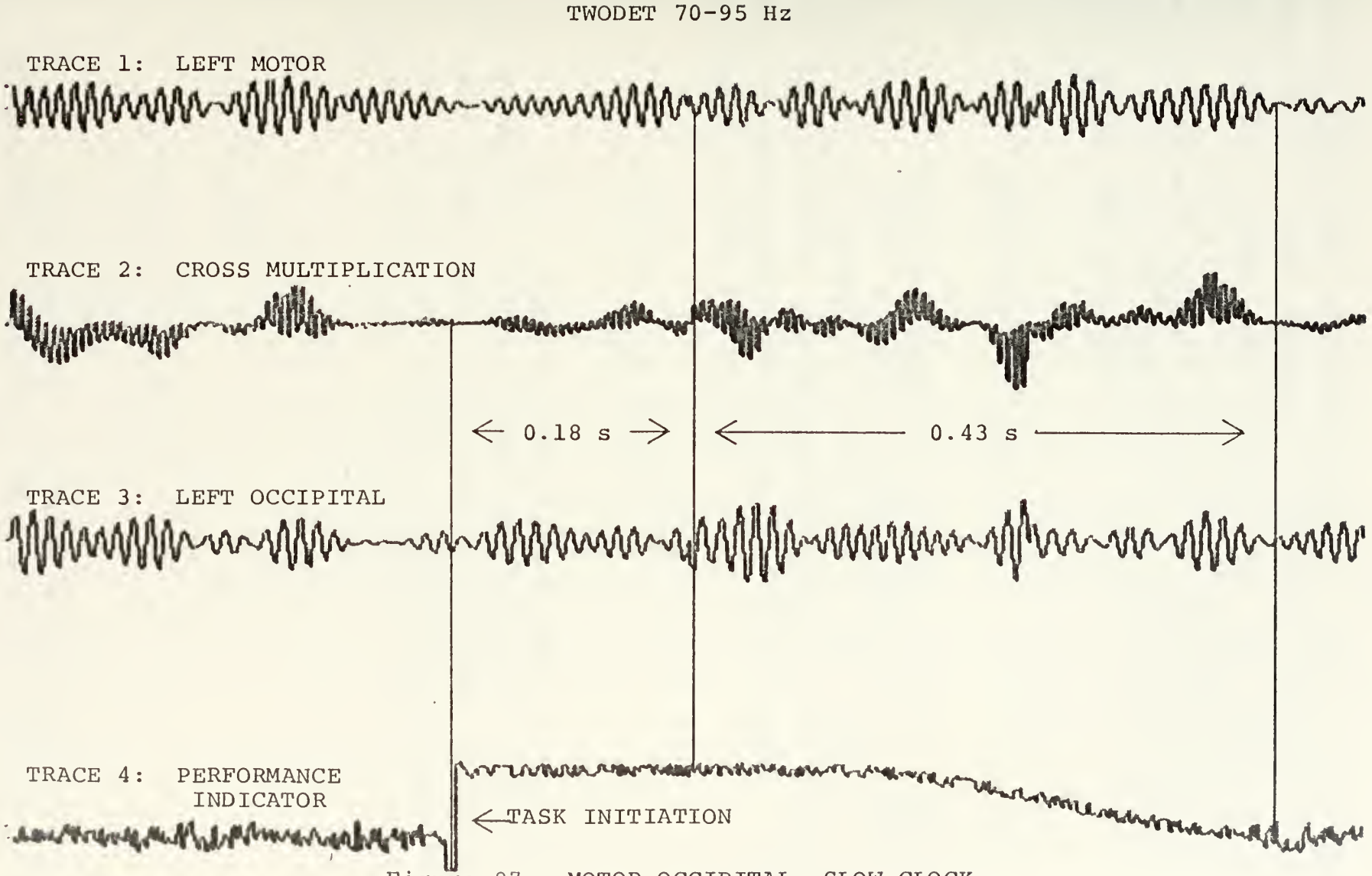


Figure 27 - MOTOR-OCCIPITAL, SLOW CLOCK

we were seeing was a response signature. After a detailed inspection of this segment, we found that 62% of the task initiations on trace 4 were followed by the signature on trace 2. Rather than one to four distinguishable positive peaks on trace 2, we observed a mix of positive and negative peaks. The delay and duration did not show much change from that of the motor-premotor.

b. Normal Stick Control, No BFB

Figure 28 presents us with another confused signature. Trace 3 shows a mix of positive and negative peaks. It was noted that, in this 100 s run segment, the response signature was characterized more by the negative peaks in cross multiplication than by positive peaks. The occurrence of signature was 54%.

c. Reversed Stick Control

The response signature occurrence jumped to 72% in this segment. This relatively high signature occurrence for the reversed stick control was characteristic of all of our runs. That we were seeing a predominately negative response signature could easily be seen in this run segment (Fig 29).

3. Fast Clock

a. Normal Stick Control

There was less activity between tasks in this run segment than in those with the slow clock. This made

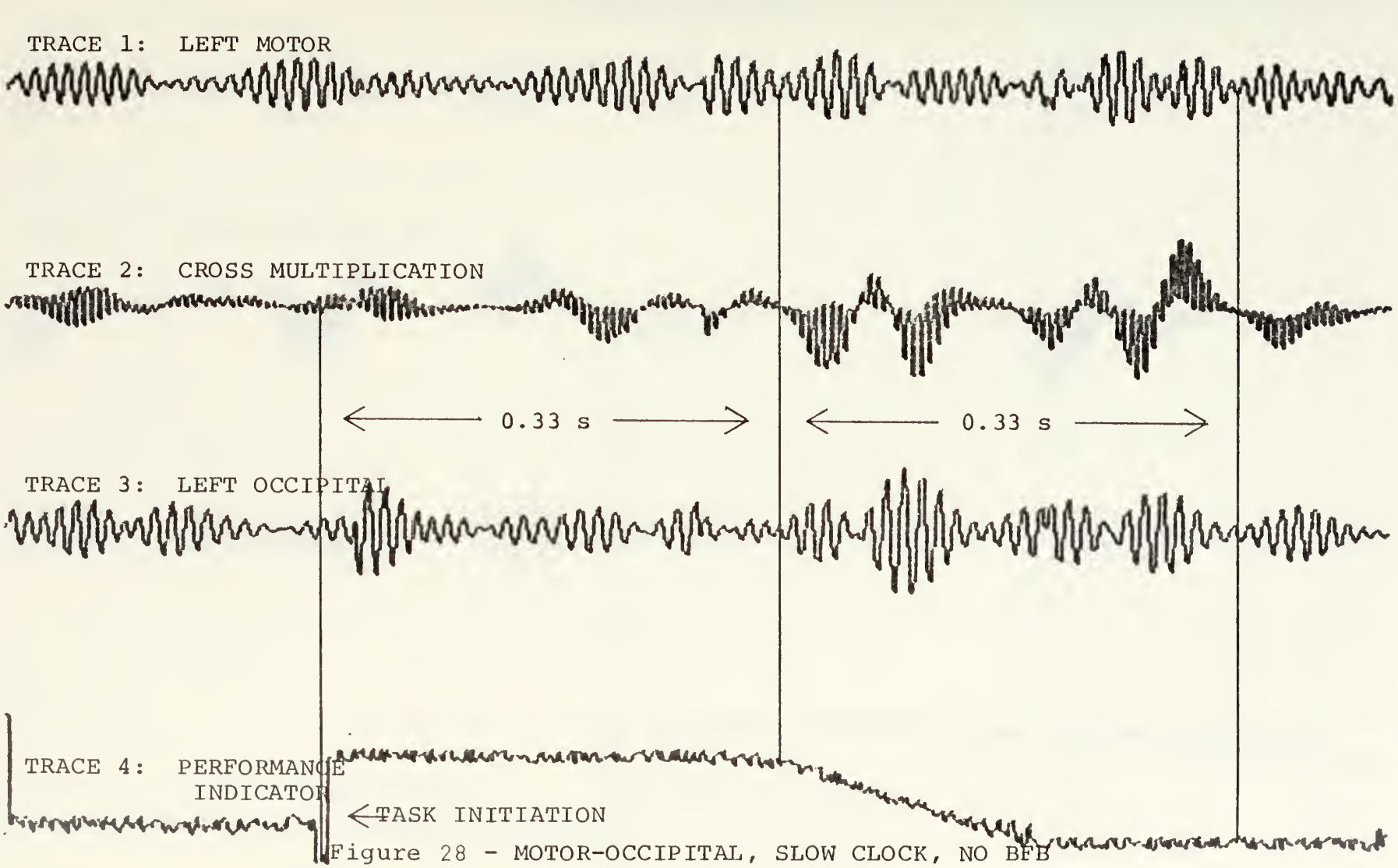


Figure 28 - MOTOR-OCCIPITAL, SLOW CLOCK, NO BFB

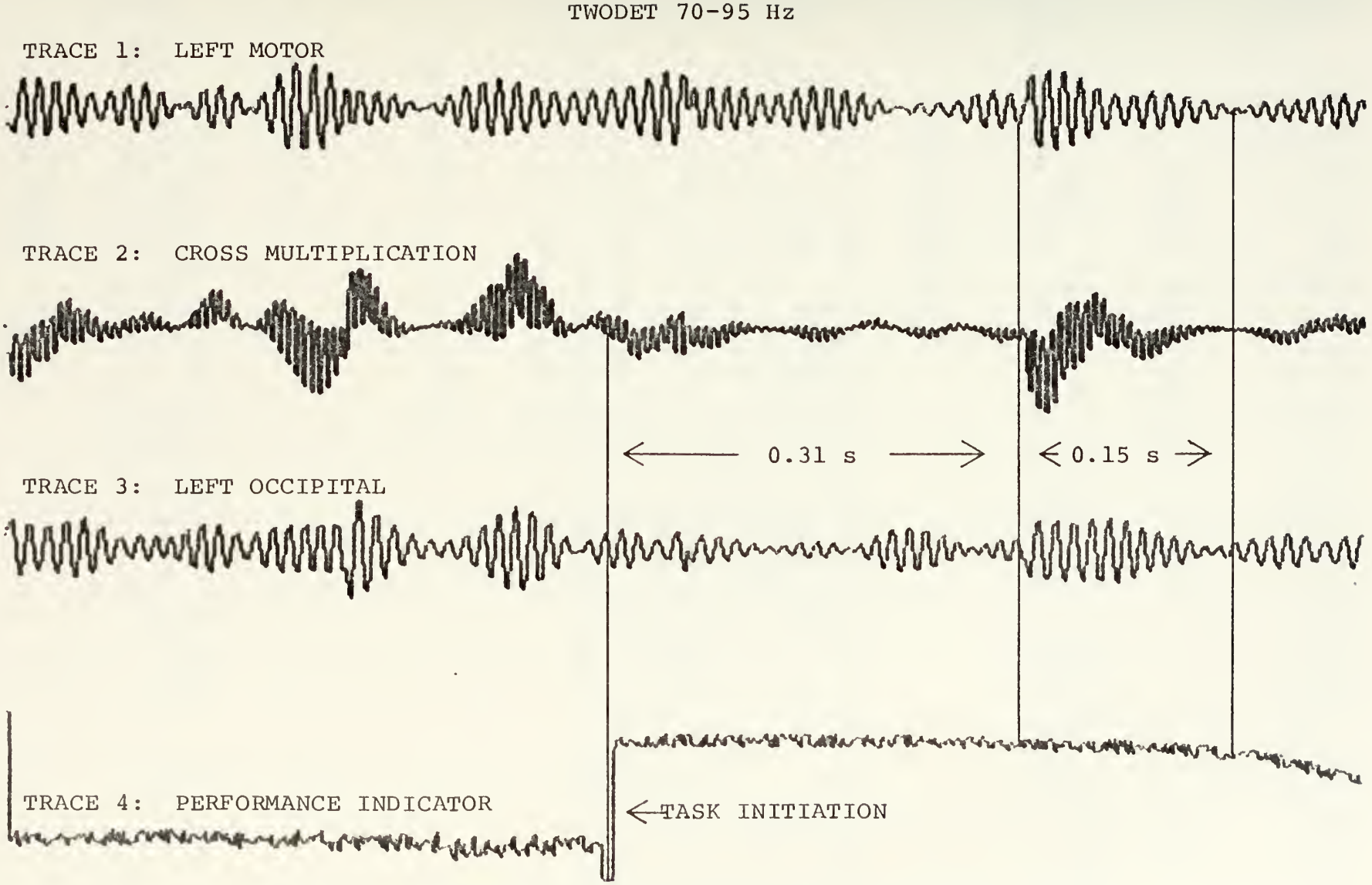


Figure 29 - MOTOR-OCCIPITAL, SLOW CLOCK, REVERSED CONTROL

the signature response somewhat more predominant, as can be seen in Fig 30. The response signature was produced by 61% of the tasks.

b. Normal Stick Control, No BFB

Once again we found the negative response signature (Fig 31). Signature occurrence was at 68%.

4. Crosscorrelation

All six runs reflected correlations of negative mean (Fig 32). Little information from this plot could be related to a detailed analysis of the run. We were certain that the wide electrode placement was the cause of the negative signal correlation. It is quite possible that we have indications of task related 70-95 Hz signal processing which propagated throughout the cortex. The negative peak signature would indicate close to 180 degrees of phase delay relative to our wide electrode placement.

F. LEFT MOTOR TO RIGHT MOTOR

1. Baseline

Although the baseline in Fig 33 displays the same random characteristics as the previous baselines, trace 2 is random in a more negative manner.

2. Slow Clock

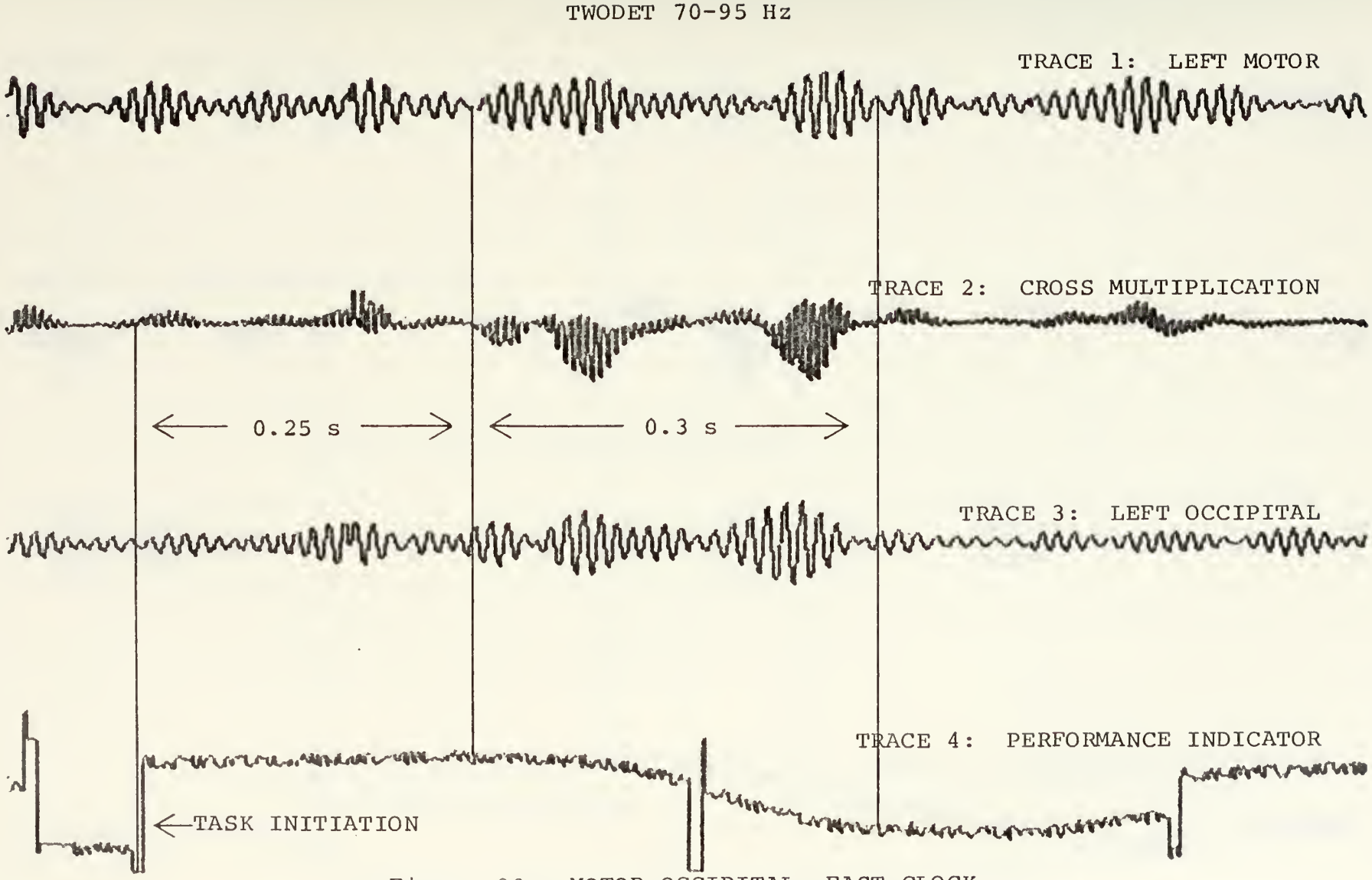


Figure 30 - MOTOR-OCCIPITAL, FAST CLOCK

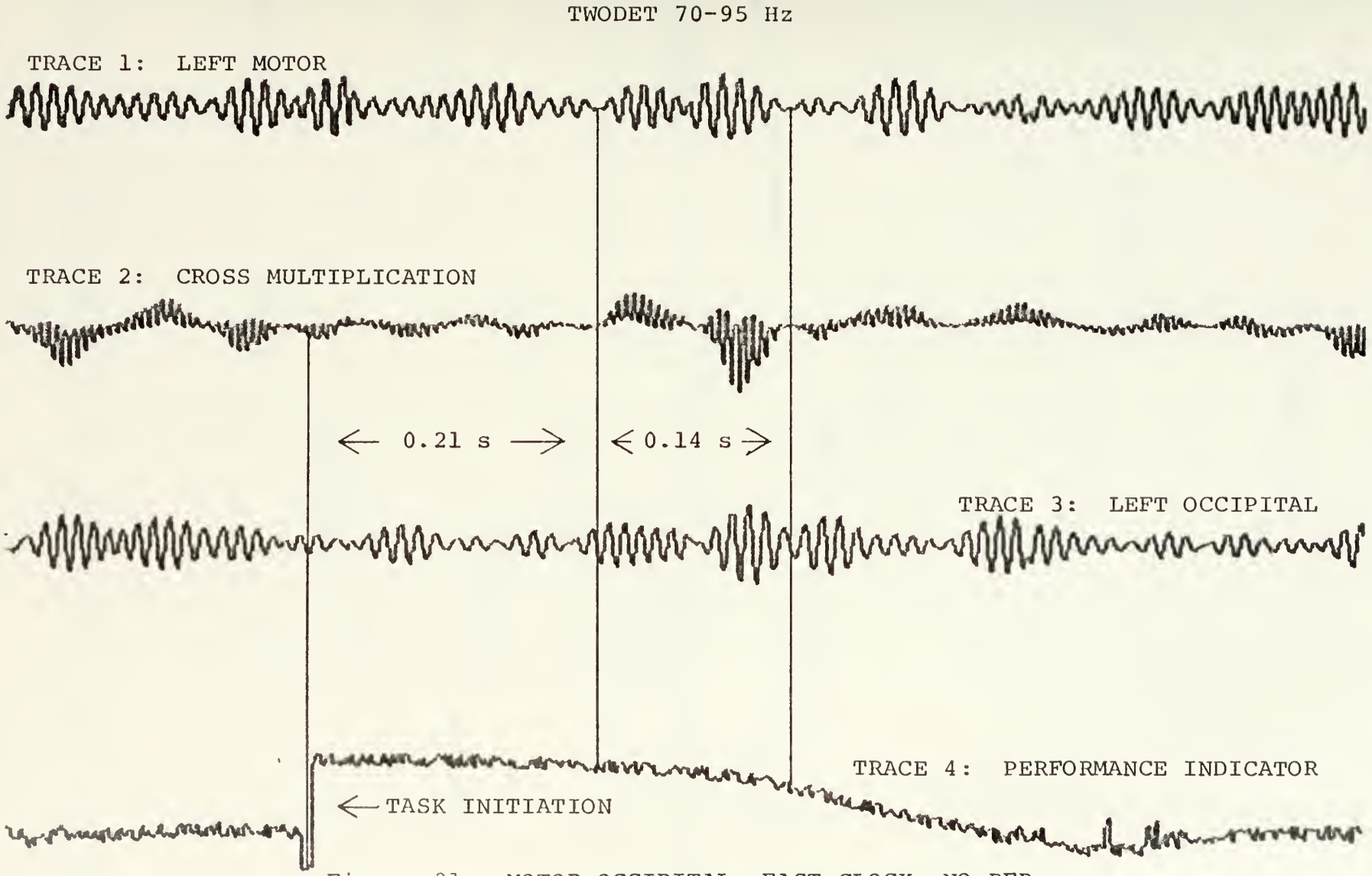


Figure 31 - MOTOR-OCCIPITAL, FAST CLOCK, NO BFB

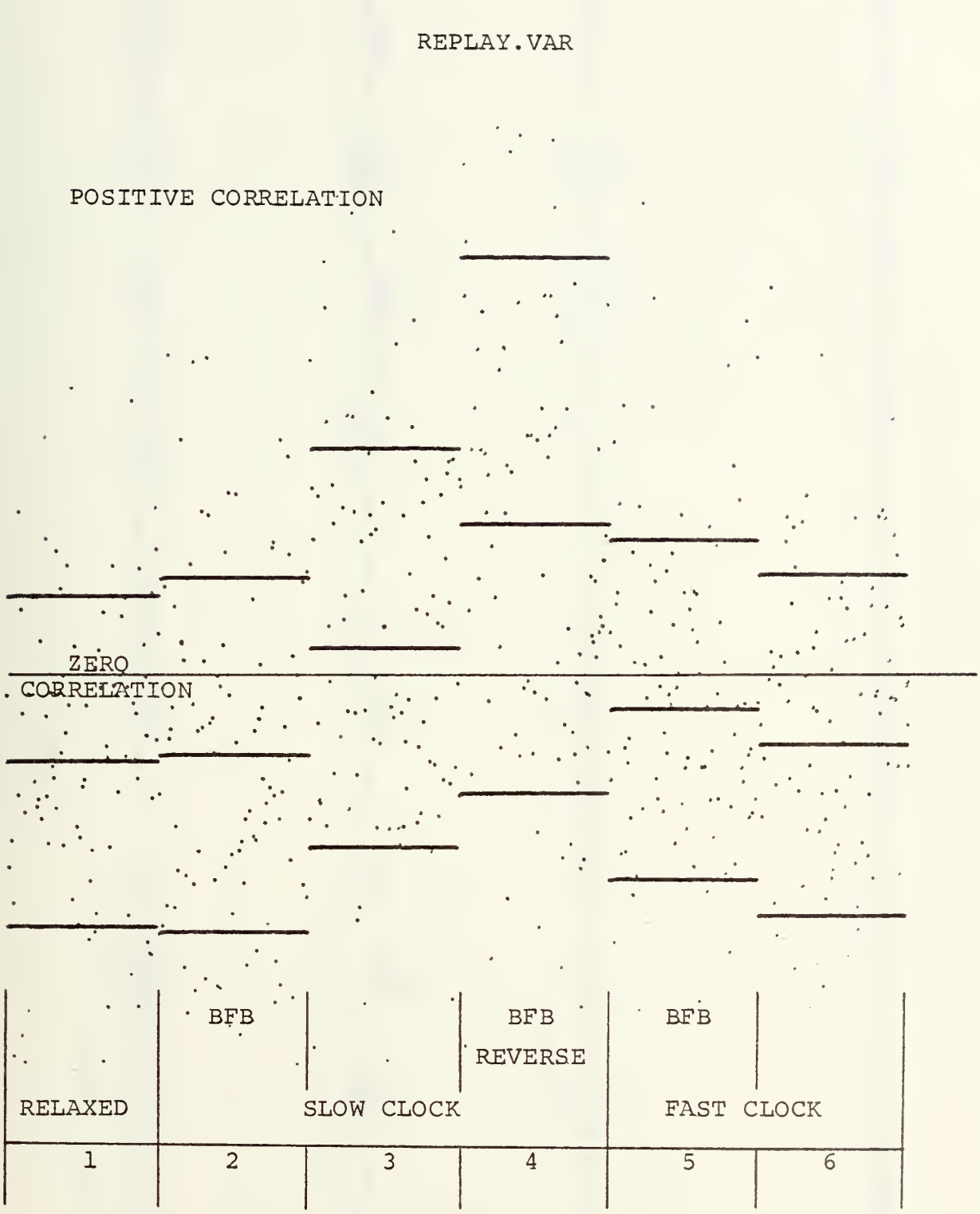
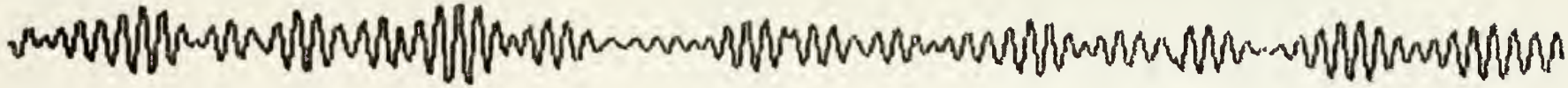


Figure 32 - CROSSCORRELATION OF LEFT MOTOR AND LEFT OCCIPITAL

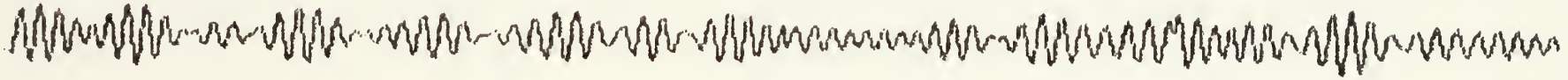
TWODET 70-95 Hz

TRACE 1: LEFT MOTOR



TRACE 2: CROSS MULTIPLICATION

TRACE 3: RIGHT MOTOR



TRACE 4: PERFORMANCE INDICATOR

Figure 33 - LEFT MOTOR-RIGHT MOTOR, RELAXED

a. Normal Stick Control

Figure 34 displays a signature response characteristic of the entire 600 s run. There was typically a quite large negative cross multiplication peak. There was an obvious difference between the tegule amplitudes of the left and right motor areas. As expected, the left motor tegule amplitudes, within the response signature duration, were larger than those of the right motor area. The subject used his right hand for the task stick control. The response signature occurrence was 45%.

b. Normal Stick Control, No BFB

The response signatures of this run segment were large negative peaks (Fig 35). 59% of the tasks evoked response signatures.

c. Reversed Stick Control

Figure 36 shows the characteristic response signature of the left motor to right motor area run. The occurrence of signature jumped to 67%.

3. Fast Clock

a. Normal Stick Control

Once again we found the negative peak(s) response signature on trace 2 as seen in Fig 37. The

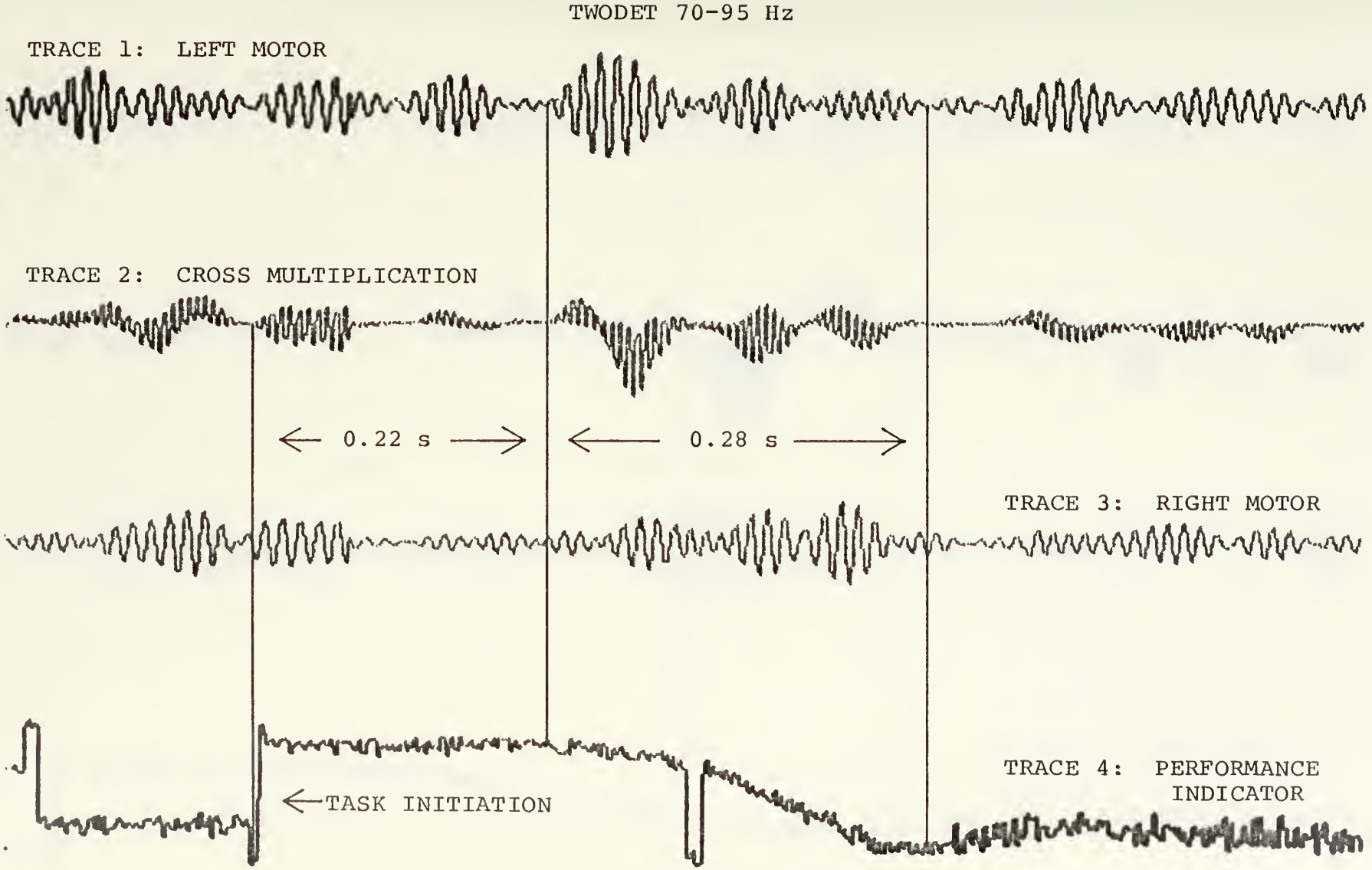


Figure 34 - LEFT MOTOR-RIGHT MOTOR, SLOW CLOCK

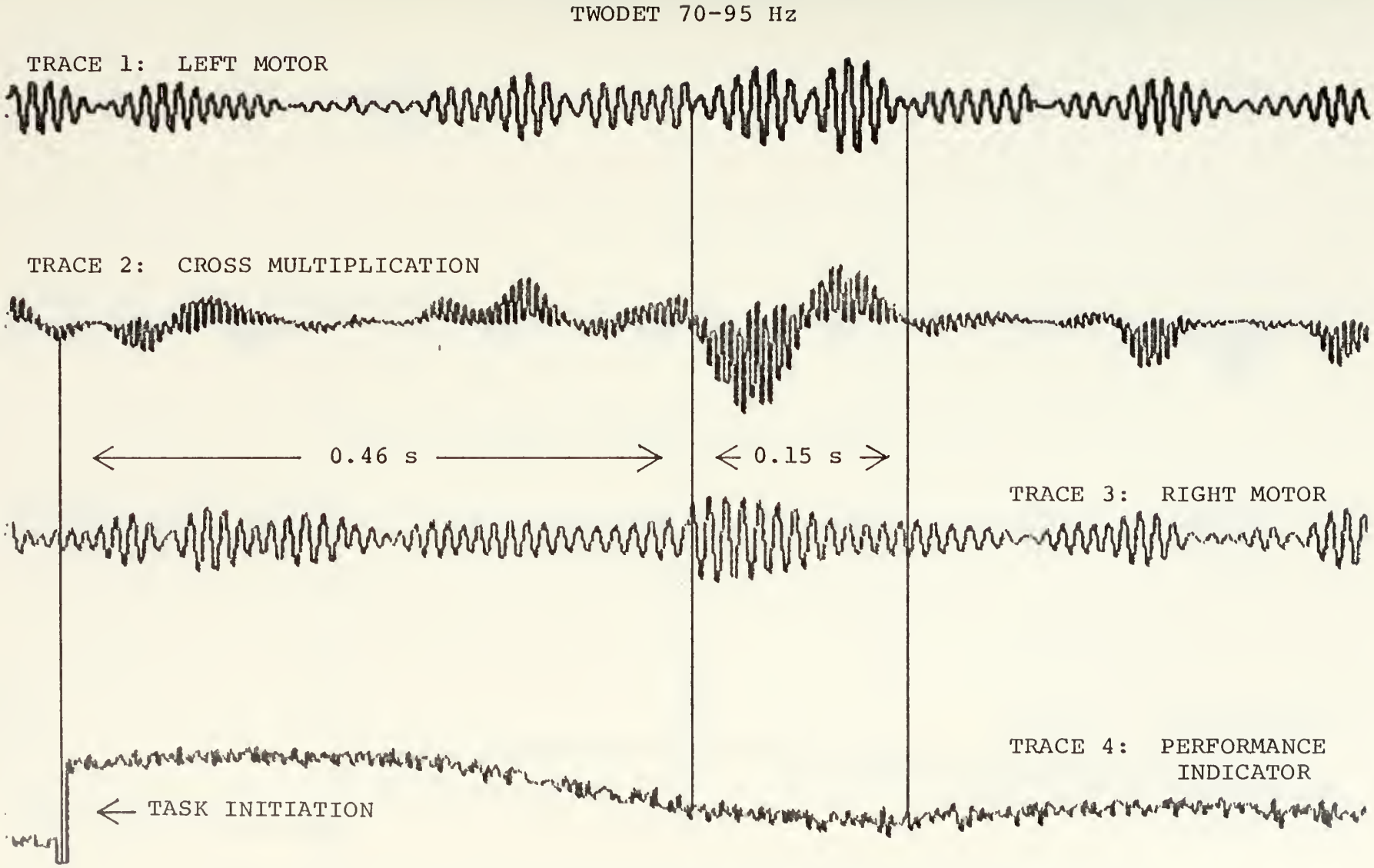


Figure 35 - LEFT MOTOR-RIGHT MOTOR, SLOW CLOCK, NO BFB

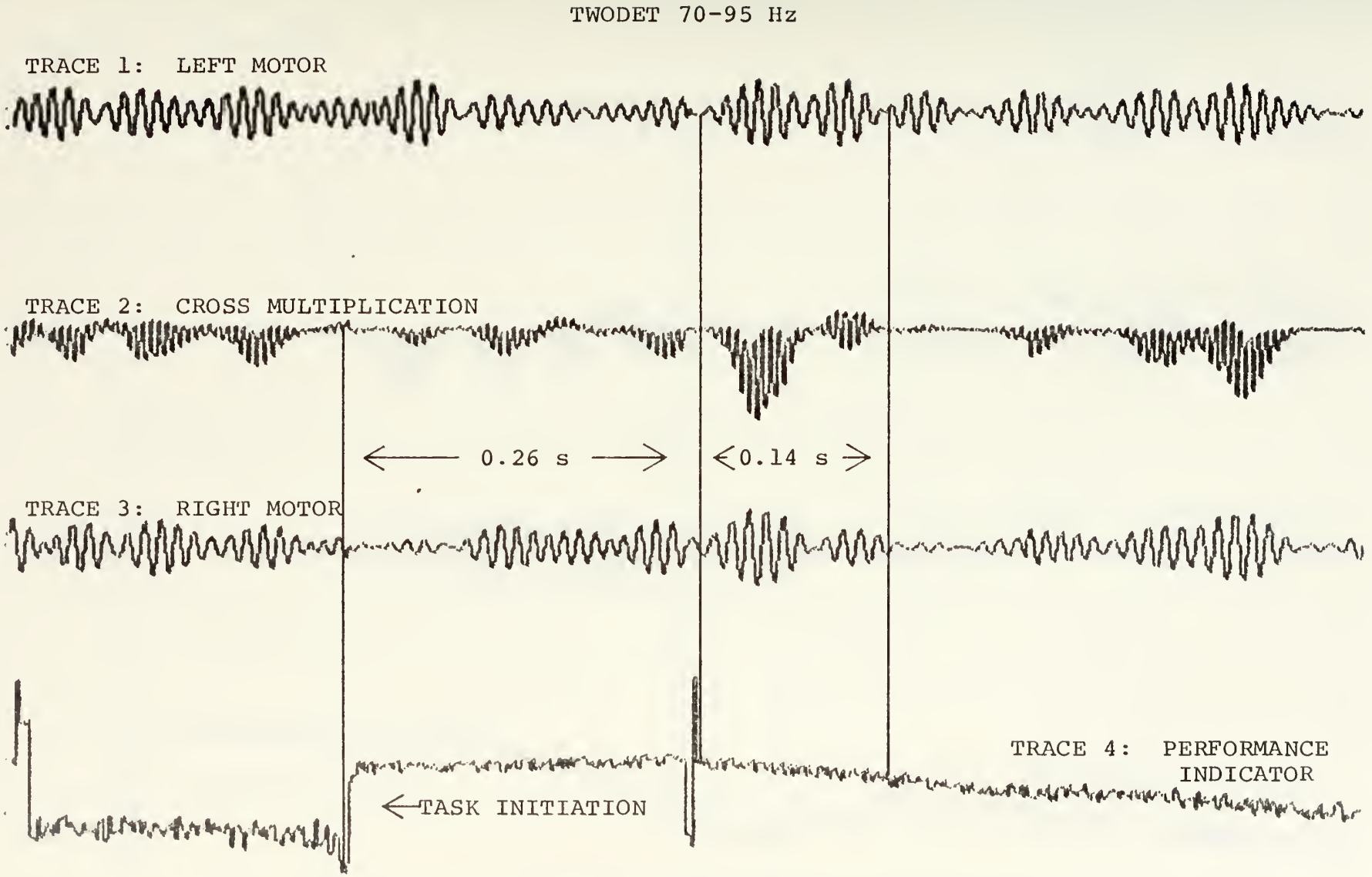


Figure 36 - LEFT MOTOR-RIGHT MOTOR, SLOW CLOCK, REVERSED CONTROL

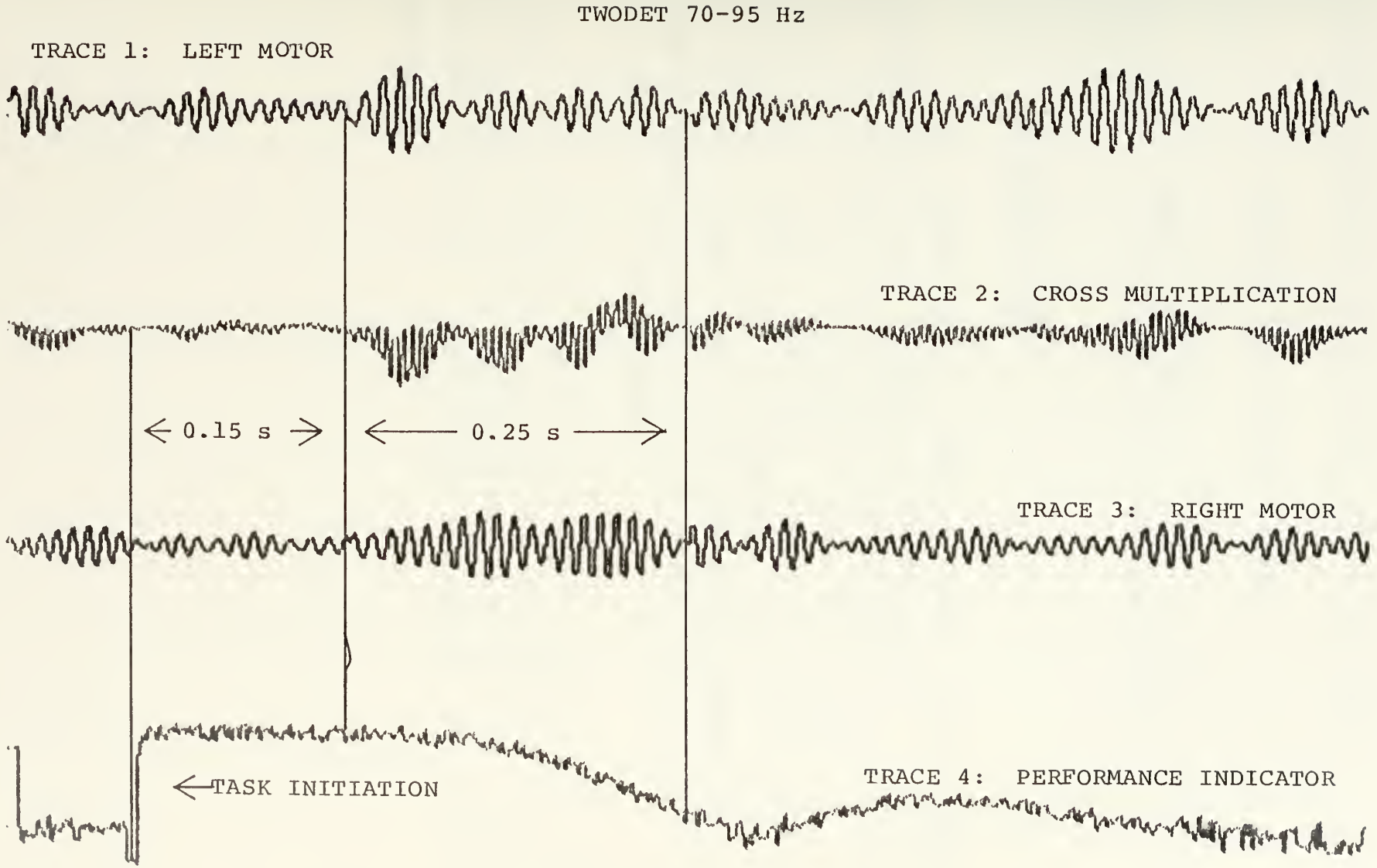


Figure 37 - LEFT MOTOR-RIGHT MOTOR, FAST CLOCK

response signature was found for 63% of the tasks.

b. Normal Stick Control, No BFB

Figure 38 shows the now easily recognized signature. The signature occurrence remained 63%.

4. Crosscorrelation

The predominately negative task related response signature was reflected in the correlation plot (Fig 39). The correlation mean for each task segment is more negative than that of the baseline. This was unique to the synchronous signal detection from the opposing cerebral hemispheres. But for one exception (Fig 14), when the primary electrodes were in the same hemisphere, the task segments generally produced a more positive correlation mean than did the baseline segment.

The response signature for left motor-right motor could be characterized as large negative peaks on the cross multiplication trace. The difficult reversed stick control segment elicited much higher occurrence of signature percentage.

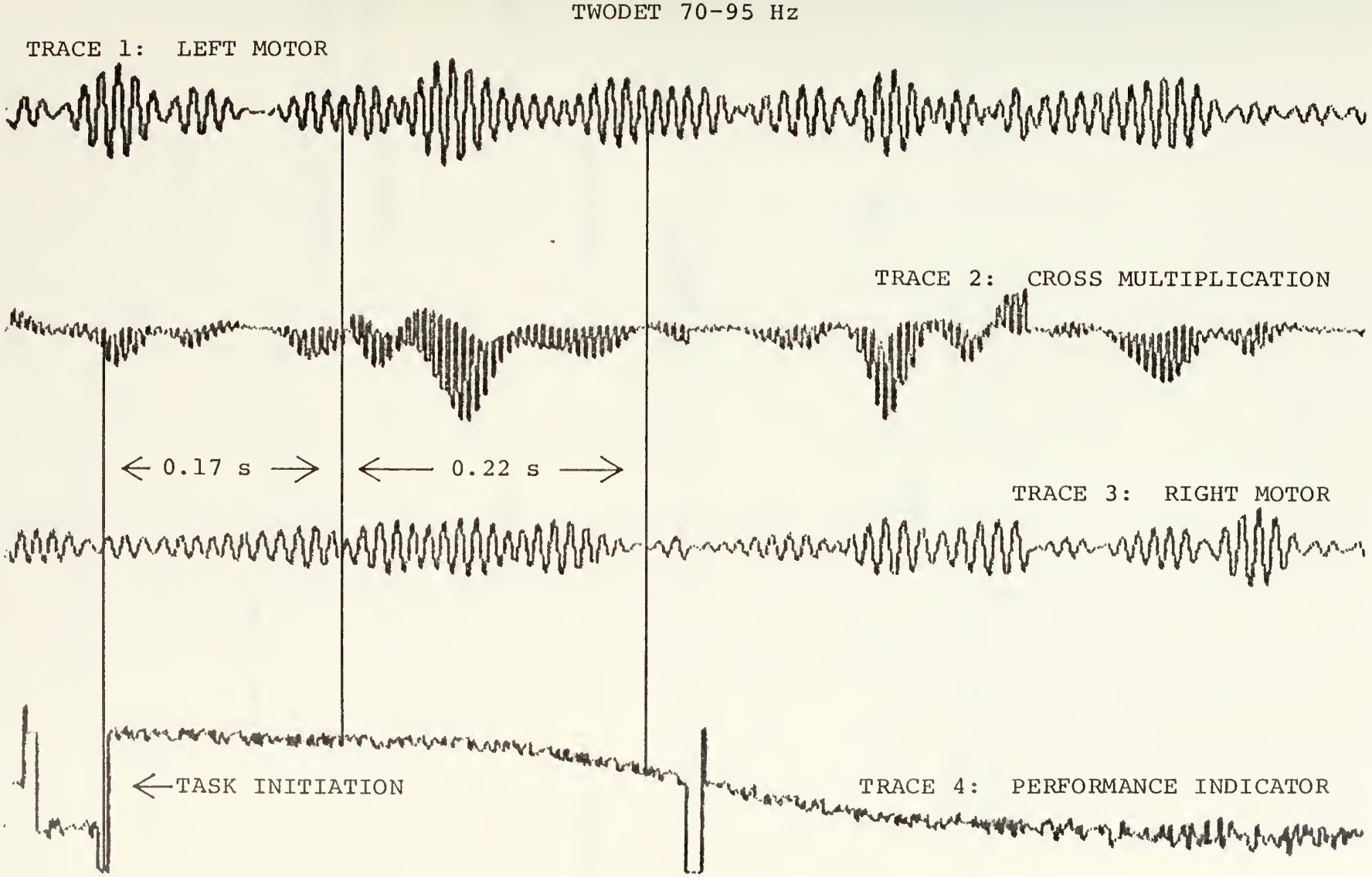


Figure 38 - LEFT MOTOR-RIGHT MOTOR, FAST CLOCK, NO BFB

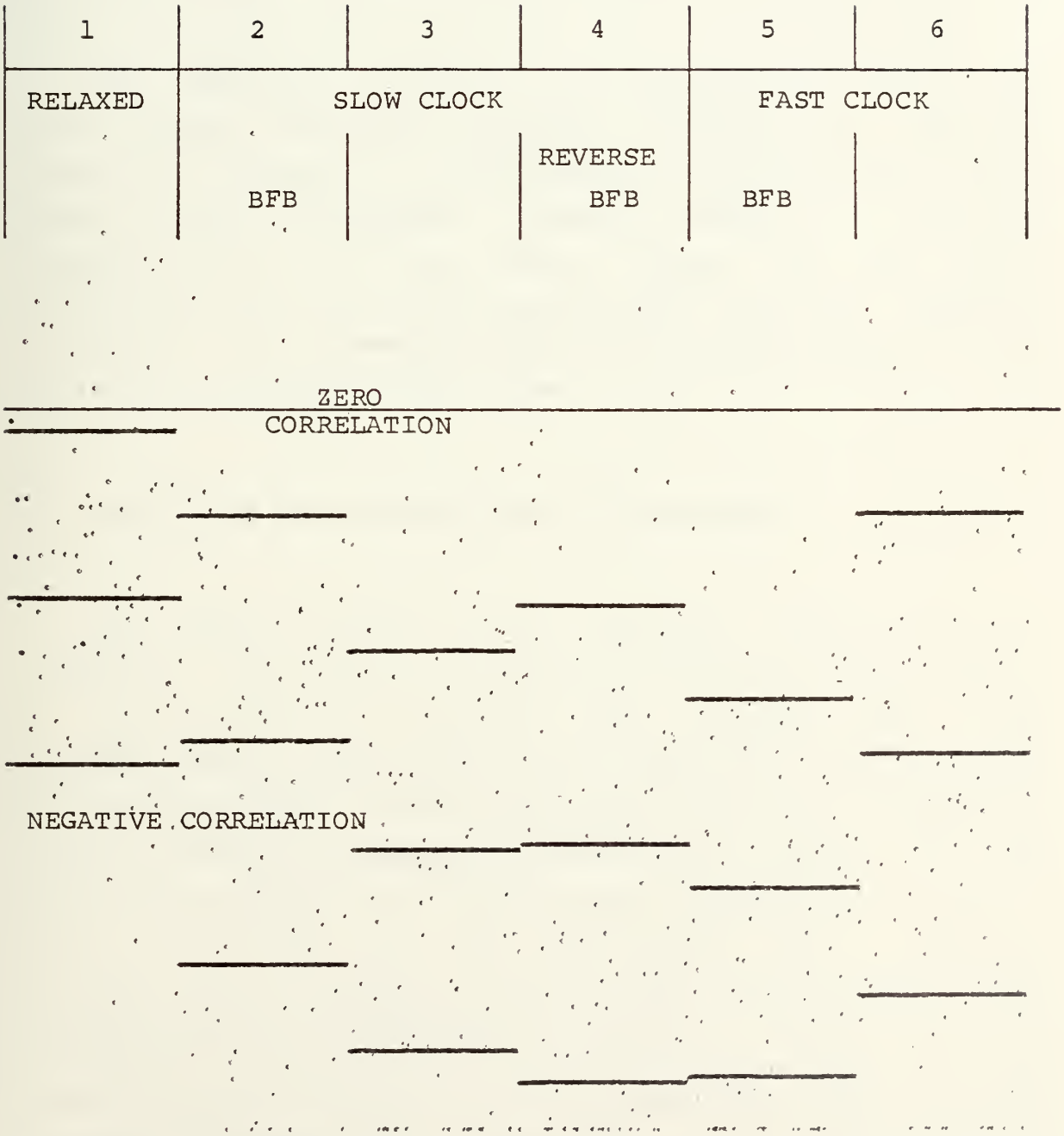


Figure 39 - CROSSCORRELATION OF LEFT MOTOR AND RIGHT MOTOR

VII. CONCLUSIONS

A. METHODS OF DATA COLLECTION

The TWODET.SAV program is an indispensable tool. The task related response signature, developed by cortical electrical signals, is graphically illustrated only after TWODET signal processing. TWODET provides the tegular representation of the brain waves and the cross multiplication of two such signals from different cerebral locations. No recommendations for the improvement of this program can be made at this time.

B. METHCDS OF DATA PRESENTATION AND ANALYSIS

The REPLAY series is an excellent vehicle for data retrieval. Any portion of any run is accessible for review on the CRO or plotting with extreme ease. The crosscorrelation plot provides the researcher with a method of trend analysis. We have utilized this plot to determine subject consistency from run to run. The presence of low amplitude products of TWODET cross multiplication tend to dilute the impact of this statistical plot. Efforts continue in an attempt to provide more significance to the crosscorrelation. REPLAY.CON is such an example whereby threshold levels pass only certain amplitude signals to the crosscorrelation routine. It is recommended that several threshold parameters be made available. One threshold could

pertain only to the non task related signals, in much the way REPLAY.CON functions. Additionally, there should be a threshold of lower amplitude keyed to the task initiation mark on the performance indicator trace of TWODET. The resultant crosscorrelation plot would operate in one of two modes. First, it would calculate the correlation of each frame of data as it does now. Second, only the portions of those frames containing the response signature would be calculated. This last mode of calculation would provide us with only the activity related data for crosscorrelation.

This research has been dependent upon frame by frame visual inspection and manual measurement techniques. While this method has been quite instructive and has provided an adequate data base for a first step into EEG task response signatures, it is too time consuming for a thorough investigation of the multivariable environment of the human brain. We require a CRO of much higher resolution than the Tektronix. Although the HP X-Y plotter is adequate for short time frame data plots, it does not provide us with a means of permanently storing long periods of data, such as a run segment. Since we have a limited number of disks, we are forced to destroy (with no long term plot record) valuable information in order to free a disk for further EEG research. This is frustrating when it sometimes takes lengthy data analysis before you know what you have seen. It then becomes necessary to reproduce the data. There is satisfaction in the ability to reproduce, but uncontrolled variables such as subject training, are present. A rapid plot system is badly needed for data storage.

C. THE TASK RELATED RESPONSE SIGNATURE

There is a response signature. The signature varies

from persen to person, but shows unique characteristics for a given individual at specified electrode positions.

We found that, by changing electrode positions, the appearance of the signature was altered. The latency and duration, however, remained relatively constant. The general characteristics of the signature are as follows:

1. random peaks and valleys,
2. task initiation,
3. delay to response,
4. positive or negative peaks of high relative amplitude,
5. low amplitude or smoothing,
6. random peaks and valleys.

1. Latency

The latency for one subject was found to be approximately 0.18 s. This varied slightly from run to run as well as from task to task, but we found no pattern of variation related to training, the task, or BFB.

2. Signature Duration

The signature duration varied only slightly from task to task. The duration of one individual's signature was 0.17 s. If the duration is dependent upon anything, other than the individual, it may be task training. There was evidence that, as the subject improved at the task, the duration increased.

3. Baseline Characteristics

A relaxed subject's EEG is completely devoid of the response signature. A baseline is a valuable reference source to which the task oriented runs can be compared. The baseline also allows the researcher to determine the normalcy of his equipment and/or subject. It might be said that the baseline is a "calibration" run. The relaxed run has already been used to calibrate the threshold in REPLAY.CON. We were able to effectively emphasize the response signature presence through careful use of the REPLAY.CON threshold parameter. This could not have been done with any confidence without the baseline.

D. BIOFEEDBACK

BFB does influence the subject's performance in the short 100 s tasked run segment. The influence of BFB caused some performance degradation. This individual felt that BFB relaxed him. Another subject reported that the BFB stimulated him. When BFB was removed, in either case, the subjects reported that they missed it. Both subjects performed the task more quickly without BFB. Further evidence of this relaxing effect (on one subject) was found when two baselines, one with and one without BFB, were run. The crosscorrelations of these two runs demonstrated that without BFB there was a more positive mean correlation than with BFB. This seems to confirm the subject's feeling of relaxation.

E. PREFERRED FREQUENCY

We continued, during this phase of EEG research, to search for those frequency ranges at which task related activity was predominant. As evidenced by the response signature, we found the highest activity to reside at 70-95 Hz. There was some indication of a shift in the preferred frequency as a result of subject training. Further investigation into this is recommended.

F. TRAINING

As the subject became more accomplished in the performance of his task, we noticed a smoothing out and a decline in the amplitude of his motor area tegules. This may very well have been a shift in the principal location of his signal processing from the motor area of the cortex to the cerebellum. If in fact this shift occurs, might we then be able to qualitatively measure the trainability of any given individual at a skilled motor function? Figure 2 showed how a motor function may be realized with much more speed and accuracy through the cerebellar initiation of motor functions.

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