A MICROPROCESSOR BRAINSTEM EVOKED RESPONSE AUDIOMETER

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by

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ABSTRACT

A Microprocessor based audiometer has been designed to carry out brain stem evoked response (BSER) tests mainly in children. A CMOS Microprocessor has been used to minimize the power consumption to enable the device to be run on batteries if required.

The Audiometer generates auditory stimuli, collects E.E.G. signal response, averages either 1024, 2048 or 4096 responses and displays or prints the result automatically. The stimuli can be generated with a variety of polarities and with accurately controlled amplitude and frequency.

Initial tests have been carried out on premature babies at the New Addenbrooke's Hospital-Pediatric Dept. (Cambridge).

A statistical analysis has been made of the correlation between averages of 32 responses against either the high level 1024 point average as the reference pattern or using the average altered according to stimulus level as the reference. The purpose of this study was to test for changes in sensitivity between the two techniques used as an objective measure of detected response in the BSER potentials.

ABBREVIATIONS

A-D.....Analog to digital

ALU.....Arithmetic and logic unit

CMRR.....Common-mode rejection ratio

CNS.....Central nervous system

cps.....Clicks per second

CPU.....Central processing unit

D-A.....Digital to analog

dB.....Decibel

DC.....Direct current

EEG.....Electroencephalogram

I/P.....Input

LED.....Light-emitting diode

LSB.....Lest significant bit

MSB.....Most significant bit

O/P.....Output

RAM.....Random access memory

ROM.....Read only memory

SL.....Stimulus level

S/N.....Signal to noise ratio

SPL.....Sound pressure level

μP.....Microprocessor

UV.....Ultraviolet

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CHAPTER 1

BACKGROUND

1.1 Anatomy of the brain.[1]

The central nervous system consists of the spinal cord lying within the bony vertebral column and its continuation, the brain, lying within the skull. Within the CNS there exist nerve tracks that act like communication links between the brain and spinal cord allowing higher centers in the brain to control or modify the behavior of the elemental spinal reflex arc at a given spinal level. Some tracks are ascending (sensory) nerve, others descending (motor). By means of such two way communication links the brain is not only informed of a peripheral event, but can modify the response of the spinal reflex to that environmental stimulus. Information is transmitted to the brain by means of a frequency modulated train of nerve impulses that upon reaching specific areas of the brain stimulate the activity of other neurons there. Similarly, the decision to implement a motor action in response to the initial stimulus is manifested in the activity of cortical neurons from various areas of the brain, depending on the particular motor action to be taken. Such

cortical activity is reflected in changes in the volume conductor field potentials recorded from the brain as EEG.

Usually the brain is divided into three main parts: cerebellum, brainstem and cerebrum. (See figure 1.1)

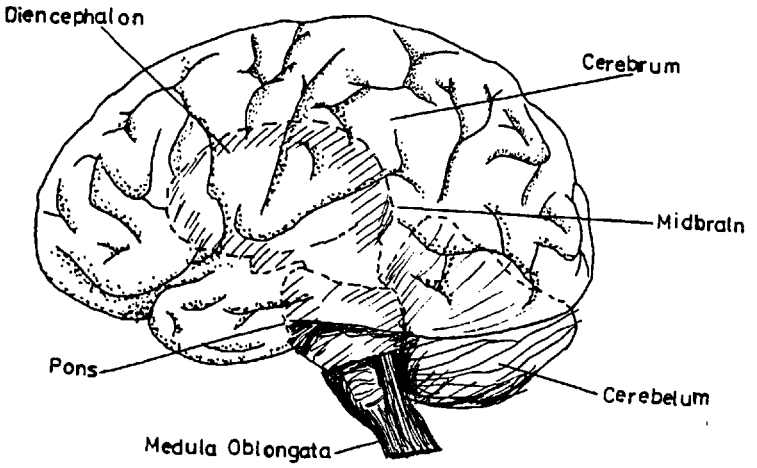


Fig.1.1 Anatomical Divisions of the Brain

The cerebellum is a coordinator in the voluntary (somatic) muscle system and acts in conjunction with the brainstem and cerebral cortex to mantain balance and provide harmonious muscle movements.

The cerebrum is a paired structure with right and left cerebral hemispheres, each relating to the opposite side of the body. The surface layer of the hemisphere is called the cortex; it receives sensory information from skin, eyes, ears and other receptors located generally on the opposite side of the

body. This information is compared with previous experience and produces movements in response to the stimuli.

The brain stem is composed of four regions, each of which has distinct functions: the medulla oblongata, the pons, the midbrain and the diencephalon. Each contains groupings of cell bodies (nuclei) and bundles of nerve axons (tracts) that are intermingled. At the upper border of the medulla is a distintive bulge, the pons. The medulla contains fibre tracts -as does the spinal cord- as well as motor and sensory nuclei for receiving sensory information from and controlling muscles in the mouth, neck and throat. It also hosts centers for the reflex control of the respiratory and cardiovascular systems.

The nerves that connect directly to the brain are called cranial nerves. There are 12 pairs of cranial nerves, 11 of which enter the brainstem (the olfactory nerve from the nose enters the cerebrum).

The pons contain cranial nerve nuclei associated with sensory input and motor output to the face.

The midbrain contains the major nuclei controlling eye movement-blinking and startle reflexes and the pupillary light reflex. It also contains rather large tracts carrying signals down from cerebral hemispheres as well as sensory tracts arising from various sources (the spinal cord, auditory system,etc.) and continuing through the midbrain to higher centers.

The diencephalon is the most superior portion of the brainstem; its chief component and largest structure is the thalamus which serves as a major relay station and integration center for all the general and special sensory systems sending information to their respective cortical reception areas.

The cerebral cortex is the functional part of the cerebrum; it is a relatively thin layer of gray matter (1.5-4.0 mm in thickness) that covers the outer surface of the cerebrum.

There are many types of cortical neurons and they are not randomly distributed along the axis normal to the cortical surface. They show an orderliness, in fact, that affects both the distribution of cell types and their packing density. Relative

segregation by depth produces a stratification; each stratum is called a cortical layer. The cortex is generally arranged in six layers consisting mainly of pyramidal cells and granule cells. The pyramidal cells have a triangular shaped body , with the base down and the apex directed toward the cortical surface. Their dendrites either cross the overlaying cellular layers and branches terminally within the outermost layer of the cortex or ramify in the immediate vicinity of the cell body, largely horizontally.

1.2 Activity recorded in the EEG.

The background electrical activity of the brain in unanesthetized animals was described qualitatively in the 19th century but it was first analysed in a systematic manner by the German psychiatrist Hans Berger, who introduced the term electroencephalogram (EEG) to denote the potential fluctuations recorded from the human brain. These recorded fluctuating potentials represent a superposition of the volume-conductor fields produced by a variety of active neuronal current generators. Unlike the relatively simple bioelectric source of a nerve trunk, the source generating the field potentials recorded here are aggregates of neuronal elements with com-

plex interconections.

It has been suggested that the rhythmic activity normally recorded from the scalp has a cortical origin being derived from the postsynaptic potentials of cortical neurons. In particular, it is the pyramidal neurons that are important in this respect, while potentials arising from neuronal activity in subcortical structures or from horizontal oriented cells contribute little, if anything, to the normal scalp recorded EEG.

1.3 The auditory pathway.

The auditory pathway is usually divided into three zones[2]: ear canal, middle ear and inner ear. (See figure 1.2)

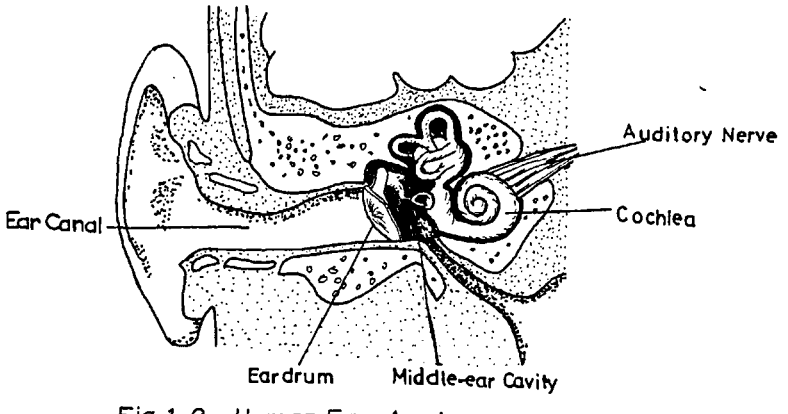


Fig.1.2 Human Ear Anatomy

The first step of hearing takes place at the ear canal. The sound waves reverberate from side to

side and produce on the tympanic membrane or eardrum a bow inward during a compression wave, and then, it returns to its original position during the rarefaction wave. The tympanic membrane separates the ear canal from the middle ear cavity. The second step of hearing comprises the transmission of sound energy from the tympanic membrane through the cavity of the middle ear and then to the receptor cells in the inner ear. The tympanic membrane is coupled by a chain of three small middle ear bones to a membrane-covered opening (the oval window) which separates the middle ear and the inner ear.

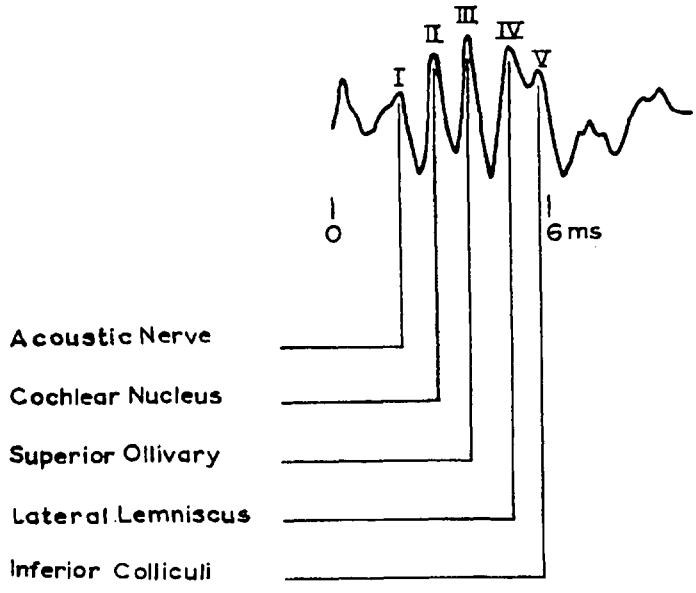
The inner ear or cochlea is a coiled passage in the temporal bone. It is almost completely divided lengthwise by the basilar membrane where the sensitive receptors that transform sound energy into action potentials are situated. The receptors are known as hair cells and their number and arrangement vary from species to species. The auditory nerve takes origin from the hair cells in various ways. The central ends of the auditory fibres divide in regular manner to send each a branch to the cochlear nucleus. The fibres which leave the cochlear nucleus all terminate in cell groups somewhere between the pontomedullary junction and the midbrain. These cell groups comprise the superior ollivary complex

together with the nuclei of the lateral lemniscus which can be regarded as forming its rostal extension. The bulk of fibres in the lemniscal pathway terminate in the inferior colliculus, but a few by-pass it to reach the medial geniculate body directly. The inferior colliculi themselves give rise to fibres the majority of which pass to the medial geniculate body. The neurons of the medial geniculate body in turn send their axons to the specific area of the neocortex called the auditory cortex.[3]

1.4 Brainstem auditory evoked responses.

1.4.1 Description.

If one could record directly from several different levels of the subcortical auditory pathway in man, one would see in the first 10 ms. following an appropiate acoustic stimulus a series of potentials corresponding to the sequential activation of peripheral, pontomedullary, pontine and midbrain portions of the pathway.[4] As shown diagramatically in figure 1.3, when these acoustic nerve and brainstem potentials are volume conducted to surface recording electrodes at the vertex and earlobe, they form a composite series of vertex-positive and vertex-negative waves known as auditory brainstem



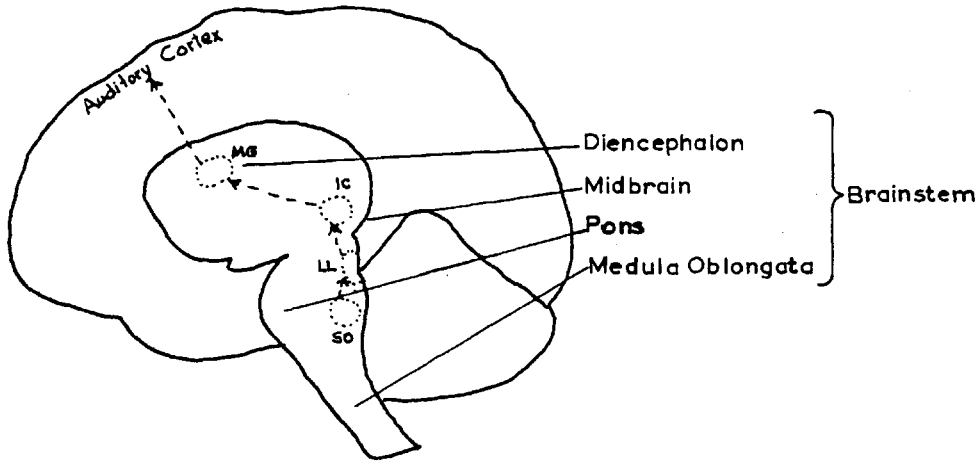


Fig 1.3. Diagramatic Description of Auditory BSER

evoked responses (BSER). The peak to peak amplitudes of the auditory BSERs recorded from the scalp are, at most, only about one one-hundredth the amplitude of the on-going EEG activity and therefore must be extracted from this and other noise by the use of computer averaging techniques. The vertex-positive (earlobe-negative) representations of the eighth nerve action potential and the four successive auditory BSERs are usually designated as waves I through V, respectively, and plotted vertex-positive-up (earlobe-negative- up).

Experimental and clinical evidence suggests that these potentials arise in or near the following structures: I, acoustic nerve; II, cochlear nucleus; III, superior ollivary complex; IV, tract and nucleus of the lateral lemniscus; V, inferior colliculi. It appears that waves I, III and V represent volume conducted electrical activity from the acoustic nerve, pons and midbrain respectively, and that the latencies between these three potentials indirectly reflect neural conduction in the corresponding segments of the central auditory pathway.

Jewett and Williston[5] (1971) were the first to fully describe the human BSERs and interpret them as

such, although Sohmer and Feinmesser[6] (1967) actually recorded them earlier and recognised the possibility of their brainstem origin. Sohmer, Feinmesser and Szabo[7] (1974) were the first to report selective alterations of different BSERs by various types and loci of posterior fossa pathology. These clinicopathologic correlations with specific BSERs abnormalities were extended over the next three years by others (Starr and Achor[8], 1975; Stockard et al[9], 1976; Starr and Hamilton[10], 1976; Stockard and Rossiter[11], 1977; Gilroy et al[12], 1977).

Some non neurologic factors influence the inter-peak latencies and relative amplitudes of BSERs. It could be worth mentioning some of them:

-Age: Below the age of about 2 years, inter-peak latencies are prolonged relatively to adult values and vary inversely with age (Hecox[13], 1975; Salamy , McKean and Buda[14], 1975; Starr et al[15], 1977). This change is not linear with age and reaches its maximum in the 32-34 week conceptional age as shown by Starr et al[15] (1977).

-Sex: Females have significantly shorter III-IV and I-V interpeak latencies than males (Stockard et al[16], 1978). This difference might be related to

shorter anatomical distances in the corresponding segments of the auditory pathway, in view of the smaller average brain size of females as compared to males.

-Stimulus phase: The initial phase of the click, either rarefaction or condensation seems to be an important determinant of BSERs. Rarefaction clicks are produced by initial movement of the headphone transducer away from the tympanic membrane, and condensation clicks result from initial displacement toward it. The common practice in many electrodiagnostic laboratories is to alternate the polarity of stimuli to minimize electrical and stimulus artifacts.

-Stimulus rate: Increasing stimulus rate increases the poststimulus latencies and also increases the interpeak latencies (Rowe[17], 1978; Stockard et al[16], 1978). However Chiappa et al[18] (1979) mention that increasing click rate from 10 per second to only 30 per second produces no significant differences.

1.4.2 Applications.

As a particular pattern of auditory BSER can be recognised in patients with normal hearing , non ex-

istence of some peaks or uncommon inter-peak latencies can be characterized as a sign for detection of some neurological disorders. But the physiological and technical variables that influence the BSERs must be controlled before applying any criteria for abnormality.

The most important clinical applications of BSER in adult neurology are[4]: i) evaluation of the cause and reversibility of coma, ii) the early diagnosis of multiple sclerosis and iii) detection of posterior fossa tumors. In children, particularly in neonates BSER tests have been used as a useful tool for early detection of auditory abnormalities.

1.5 Coherent Average Technique.

Since the recording of EEG signals is done with electrodes applied to the surface of the skin, many problems emerge. The main problems arise because the electrodes pick up not only the small amplitude of the response itself but also the large amplitudes of other biological and electrical activity, this is in fact a problem of small signal to noise ratio. To increase the signal to noise ratio an ensemble average technique is used; this consists, generally

in adding coherently (i.e. in a time synchronised way) an ensemble of post-stimulus signals, as many times as a stimulus mark is generated indicating the beginning of each addition cycle. This technique relies on the assumption that the response pattern would be virtually identical each time an effective stimulus is presented while the background activity should be uncorrelated, so the coherent portions of the responses reinforce each other when added and the non coherent response or noise adds randomly and therefore tends to cancel out.

Assume that the ith. post stimulus EEG record is $f_i(t)$ and comprises the sum of a response component $s_i(t)$ and random unstimulated background activity $n_i(t)$. Assume further that the coherent average of N post-stimulus record is $z_N(t)$ and that the response is identical each time,

$$f_i(t) = s_i(t) + n_i(t) = s(t) + n_i(t)$$

$$z_N(t) = \frac{1}{N} \sum_{i=1}^{N} f_i(t)$$

The average value of $z_N(t)$ assuming infinitely many repetitions of the measurement, is

$$\langle z_N(t) \rangle = \langle \frac{1}{N} \sum_{i=1}^{N} f_i(t) \rangle$$

$$= \langle \frac{1}{N} \{ \sum s(t) + \sum n_i(t) \} \rangle$$

$$= s(t) + \frac{1}{N} \langle \sum n_i(t) \rangle$$

$$= s(t)$$

if the noise has zero mean.[19]

If the variance is considered, it can be shown that the variance $\sigma_z^2(t)$ of the coherent average z(t) is $\sigma_N^2(t)/N$, that means that in terms of variance the result of averaging N responses leads to an improvement of N times on the signal to noise ratio, therefore, in rms terms an improvement of $\sqrt{N}$ on the S/N ratio is achieved.

1.6 Patient safety.

When a person is connected to electrical apparatus, he has to be guarded against the risk of electrical shock. The main risk is leakage of mains currents into the person, either by capacitive connections through the mains transformer or by direct contact such as might occur if the live lead becomes

disconnected and touches a vulnerable point in the circuit. The electrical paths are provided in this case by the electrodes connected to the patient.

The effects of currents flowing through a human being when the contacts are made externally from limb to limb are described below.[20]

The threshold of electrical perception in humans is situated around 2 to 10 mA. For higher levels nerves and muscles are vigorously stimulated eventually resulting in pain and fatigue. A "let go current" has been defined as the maximun current for wich the subject can withdraw voluntarily. Still higuer currents cause involuntarily contraction of respiratory muscles severe enough to cause asphyxiation if the current is not interrupted. Currents between 75 to 400 mA can produce a life-threatening physiological phenomenon, known as ventricular fibrillation, this consists of a lack of coordinated action among the muscle fibres of the heart which defeats its ability to pump blood. Unfortunately it does not stop when the current that triggered it is removed. Normal rhythmic activity will return only if a brief high-current pulse from a defibrillator is applied to simultaneously depolarize all the cells

of the heart muscle. After all the cells relax together, a normal rhythm usually returns. When the current is in the 1 to 6 A range the entire heart muscle contracts, but the normal rhythm ensues when the current is interrupted, just as in defibrillation. Higher currents usually cause burns, the brain and other nervous tissues lose all funtional exitability.

The minimum current that could cause any threat to a human life is relatively high (75 mA for fibrillation), however it has to be pointed out that this is when the electrical contacts are made externally and this value decreases considerably when the contacts are made internally in the body. For instance, it has been found that 20 μA flowing between the right and left ventricles in hearts of dogs can cause ventricular fibrillation. Since a similar value is expected to be found on humans, some safety standards for medical instruments have been set up with the aim of reducing the risks of high currents flowing through the patient.

One technique recommended to safely carry out bio-electrical measurements from a human being is to make floating all the parts of apparatus connected

to the patient. In this way the patient is completly isolated from the mains. So, if a live mains lead touches the patient, he is protected because there is no pathway for the current to flow through him to earth via any of the apparatus to which he is connected.

The scheme on figure 1.4 shows a typical floating amplifier that has been used in the design of the BSER Audiometer.

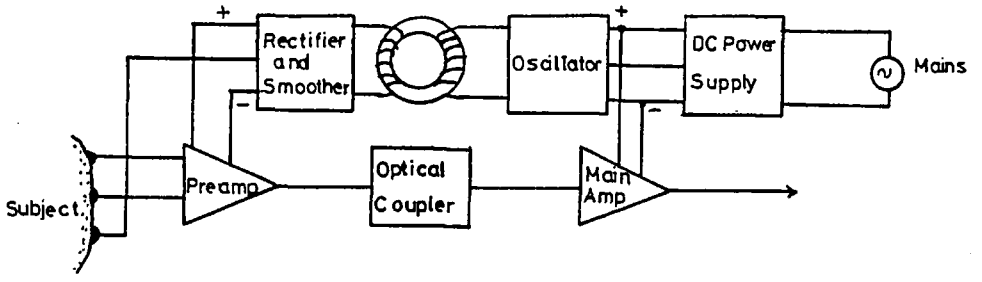


Fig. 1.4 Patient Isolation

The DC power supply of a conventional type fed from a mains transformer is used to power the oscillator, the secondary of the toroid is then rectified and filtered. The two windings are kept physically separated from each other. The preamplifier is powered by the isolated DC values. The signal coming out from this preamplifier is transferred to the main amplifier optically.[19]

CHAPTER 2

INSTRUMENT DESCRIPTION

2.1 Introduction.

The process of obtaining the auditory BSER can be summarized as the generation of a stimulus and the recording of the EEG signal response. The measurements are usually done in the following way: The first thing to be done with some care is the placing of the EEG electrodes on the scalp and earlobes of the patient. Generally the silver-silver chloride type are used; they are stuck to the skin, which has to be previously cleaned with an antiseptic solution and then the space remaining between electrodes and skin is filled with electrode gel to establish good contact between skin and electrode. The three electrodes are placed as shown in figure 2.1, one on the vertex, corresponding to the active line; the two others are located each on one earlobe, with the one corresponding to the reference line on the side where the earphones are to be applied.

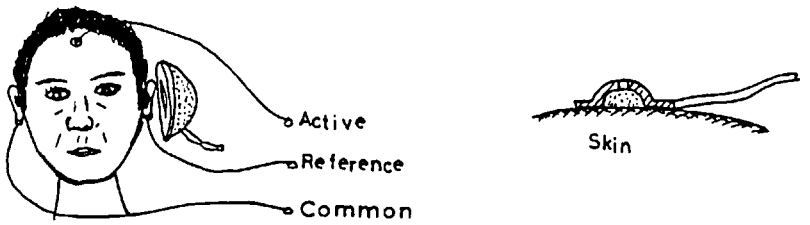


Fig. 2.1 Subject Wiring and Electrode Detail.

Then the impedances between electrodes are measured and their values expected to fall below 5 KΩ. The EEG signal is normally about 10 μV amplitude, this means that a large amount of amplification has to be performed before actually working with that signal. It is advisable to have the possibility of a variable gain, as some variability on the EEG between patients is likely. A choice regarding the different parameters involved in BSER recordings has to be made. This relates to the settings of the filters and the amplification of the EEG signal; polarity, repetition rate and sound pressure level of the stimulus. After the generation of a fixed number of clicks, usually about 1000, and their corresponding EEG responses have been added, the average is performed and displayed.

It was suggested that an instrument able to perform the operations just described could be designed and developed with the purpose of using it as a clinical tool for BSER measurements and applica-

tions. The general features of the instrument which has been designed are shown in the block diagram in figure 2.2, and described below:

-It is a portable instrument able to be run on batteries if needed. The advantage is that patients do not have to be necessarily moved when a recording is to be taken.

-The minimum EEG amplification is $2*10^5$; an externaly controlled multiplier factor is provided allowing amplifications up to $70*10^5$. The recordings are made taking into account the electrical safety regulations. The EEG signal is band filtered at a high cut-off frequency of 2.5 KHz, and a low cut-off frequency of either 30 or 250 Hz.

-It generates stimuli of three different shapes: positive, negative or alternately positive and negative.

-The stimulus generation rate is either 10, 20 or 30 per second.

-The stimulus sound pressure level can be set from 100 to -10 dB in steps of 10 dB, where 0 dB corresponds to the threshold of hearing.

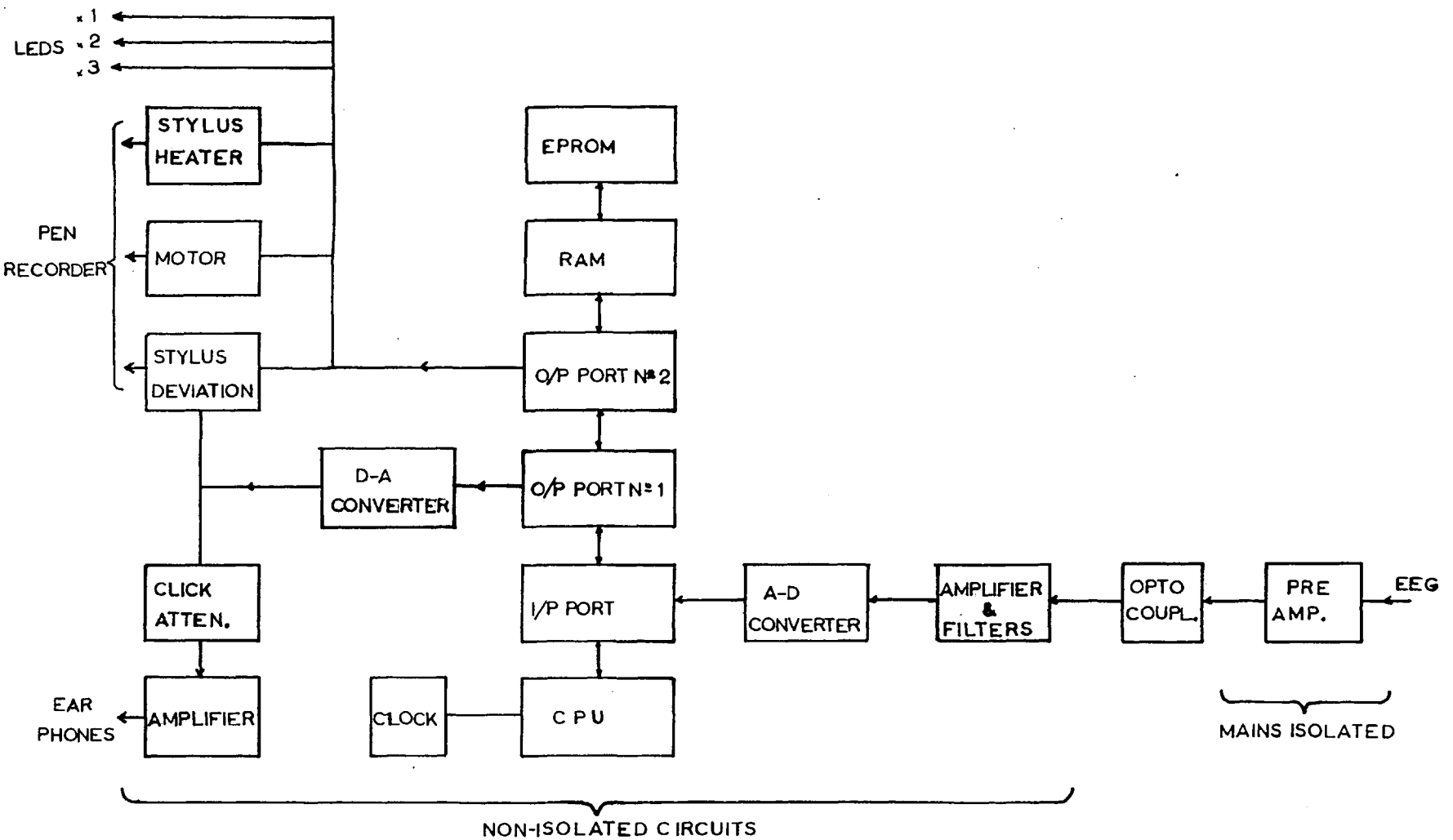


Fig. 22 - BSER Audiometer Block Diagram.

-It samples the EEG signal at a rate of 10 KHz over a length of 16 ms immediatly after the stimulus. This is adequate for the 2.5 KHz upper frequency limit of the signal, but is not so high as to require an excessive amount of storage.

-It adds either 1024, 2048 or 4096 responses and gives the average.

-There is a facility for printing the resulting average. A thermal writing strip chart DC recorder is used. Also, the response is made available for repetitive display on an external oscilloscope. For that purpose, a synchronizing signal is provided.

It was decided to use a microprocessor to control all the processes. The one chosen is the RCA 1802. This is because it is a CMOS component, thereby the power consumption is relatively low. This applies to the other support components too, as it was in mind to have a device able to be run on batteries. Though a complete information about the RCA 1802 is available from the catalogues, an introduction to the features used in the present design has been included in this thesis. The main difficulty while developing the software was the lack of suitable cross assembler facilities at that time at

the college.

The EEG amplifier has been built in two parts, one is electrically isolated from the mains and is kept in a separated screened box. This is optically coupled to the other half which is powered from the main system supply. The leakage currents are well below the maximun permitted by the electrical safety standards. A suitable A-D converter had to be chosen on the grounds of low power consumption and conversion time being less than 100 μs. A device manufactured by National Semiconductors, the ADC 0802, fulfills these requirements, and it is used in the present application.

To be able to perform the coherent average, any defined sampled point after the first stimulus should be synchronized with its equivalent points after each of the other subsequent stimuli. The acquisition of EEG data has been designed to avoid the possibility of de-synchronization because the click generation and the conversions that take place afterwards are μP controlled.

As 1024 values are added, more space than a single 8 bit memory location is assigned to hold the

result. In general, when 2^n 8-bit words are added the result can be up to n bits longer than the operand length. In the case of $1024=2^{10}$, a location up to 18 bits long could be required to store the addition result, this is accomplished assigning 3 8-bit memory locations to each sampled point. Since 16 ms of record are stored, a total amount of 160*3 8-bit memory locations are needed.

The BSER Audiometer is designed to work as follows: First, after the electrodes have been properly placed, the choice of the stimulus frequency, shape and sound pressure level, EEG amplification and filter have to be made. The earphones used are Telephonics TDH-39. When the process is started, the generation of 1024 clicks and the acquisition of their EEG responses are carried out, when that is over, the instrument responds by switching on a LED labelled "Times *1". At this moment a repetitive scan of the averaged response is available for oscilloscope display, no external control is required for this. A printing of the averaged response may be requested by pressing the push button labelled "PRINT", which activates the software control for the pen recorder; this includes first a signal to switch on the stylus heater, then the motor is started and after about .7 s delay, the response is

printed. The 16 ms of record is printed over a length of 12 cm, where the origin corresponds to the trailing edge of the click. The printing takes about 4 s., when it is over, if the motor is inmediatly stopped part of the response will remain inside the pen recorder making necesary to pull it out by hand. To avoid it, the motor is allow to run for a few seconds, to allow the piece of chart containing the response to emerge completly. No limitation regarding the number of printings exists.

After the generation of 1024 clicks, the operator may decide to generate another 1024 clicks and add their respective responses to the ones already stored, with the purpose of improving the S/N ratio; again at the end, a LED advises the termination and the instrument is at a similar status to the one described before. Further repetition is possible, in this case 2048 further clicks can be generated. The LEDs tell the number of times 1024 responses have been added, either 1, 2 or 4; these numbers are powers of 2 (10, 11 and 12), which means that a division by 2 is equivalent to shifting the data one bit to the right, making faster this kind of operation. A "RESET" push button is provided to allow a stop of any operation currently carried out; when the device is started again, all the memory locations are

cleared.

The request for a printing, as well the one for further click generation is aknowledged by the μP by the changing status of two flags. The click signal and the averaged response are both μP generated but they are intended to go to different circuits; to avoid the existence of an operator controlled switch, a 4066 Quad switch is used, which automatically routes the signals to the appropriate circuits. Also this device controls the signal being monitored by the oscilloscope, first the EEG signal and then the averaged response.

The μP comunicates with the external circuits by means of I/O ports. One is used as input port, allowing the μP to read the digital values of the EEG signal and also those corresponding to the click frequency and shape. The information about the specific click frequency and shape required is fed to the μP in digital form. Two 2-way 3 position switches perform this task, the 4 bits are then separated and stored in memory. Two output ports are required as two different signals, taking place at the same time are provided by the μP. One is either the click signal or the averaged response, and the

other the different controls for the pen recorder, LEDs and quad switch.

2.2 Microprocessor description[21]

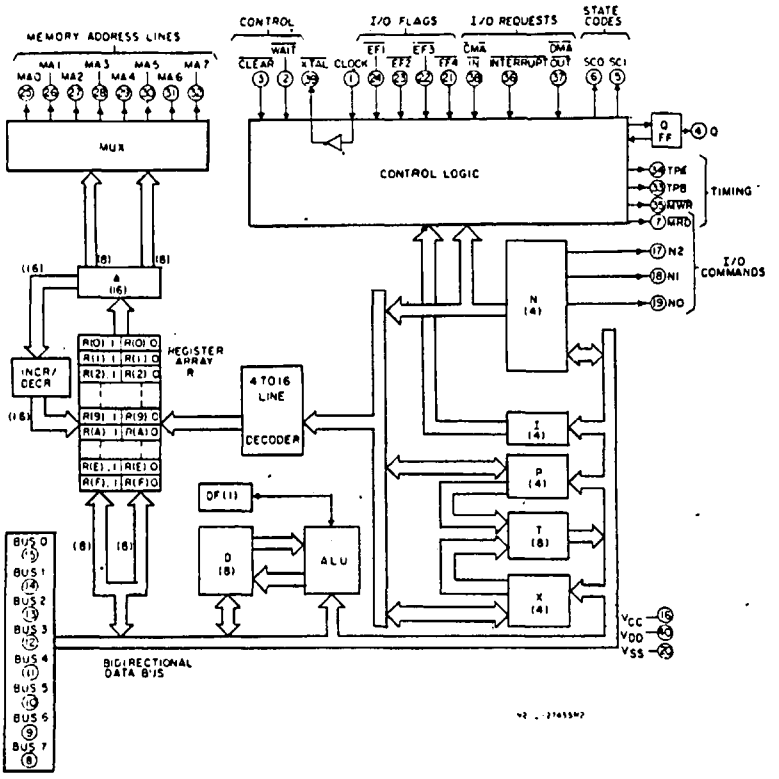


Fig. 2.3 RCA 1802 Architecture.

The RCA 1802 microprocessor architecture is shown in fig. 2.3. Its main feature is a register array (R) consisting of 16 bit scratchpad registers. They are individually selected by one of the four bit registers labelled N, P or X.

The 1802 μP instructions consist of two or three machine cycles. The first is called the fetch

cycle and the second and third, the execute cycles. A machine cycle is 8 clock pulses long. In the present application a 3.2 MHz. crystal is used as a clock, making each instruction cycle either 5 μs or 7.5 μs long.

The function of the P register is to act as a program counter. During the fetch cycle its 4 bits select one of the 16 scratchpad registers (R(P)) as the program counter. The selected register contains the address of the memory location from where the instruction is to be fetched.

The register X selects one of the 16 scratchpad registers to point to a memory location for an operand or data in certain ALU or I/O operations.

The register N can perform different functions depending on the instruction fetched. Its function is to control the X and P registers, designate one of the 16 scratchpad registers during register operations, control the selection of a specific I/O device and also, work as a pointer for certain instructions.

Another function of the R scratchpad register other than being selected either as a data pointer or as a program counter, is to act as a data register, in which two bytes of data can be held. For that purpose 4 instructions are available allowing the accumulator D to receive from or write into either the high order or the low order byte portions of the register designated by N. By using increment or decrement instructions, such registers may be used as a loop counters. The registers used in the BSER Audiometer software are:

R (2): Shift counter

R (3): Data register 80 A0

R (4): Program counter

R (5): Data register 00 03

R (6): Counter

R (7): Control locations pointer

R (8): Counter

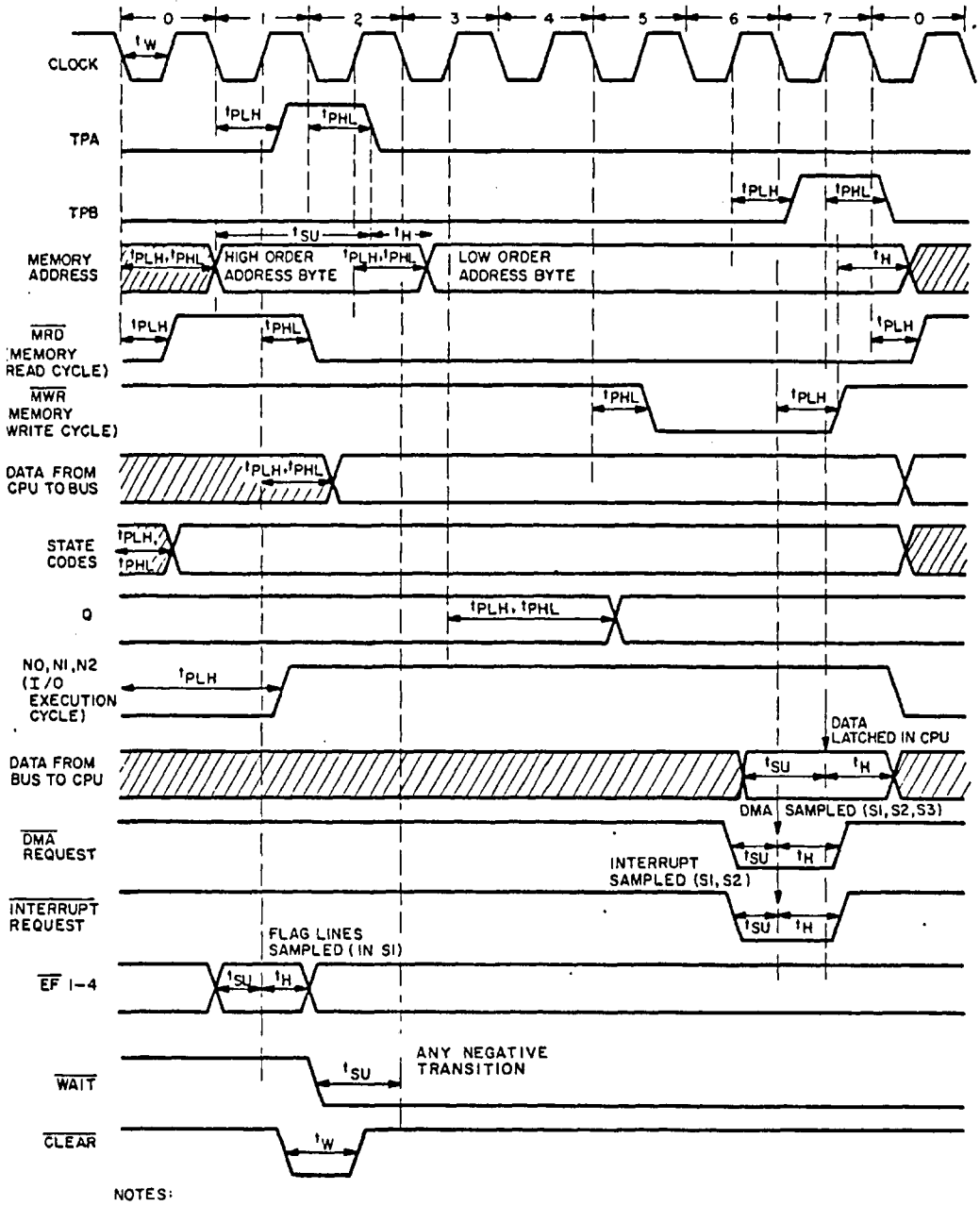
R (9): Data pointer

R (A): Counter

R (B): Counter

1802 μP signal description (See fig. 2.4):

-Bus lines : 8-bit bidirectional data bus



NOTES:

1. THIS TIMING DIAGRAM IS USED TO SHOW SIGNAL RELATIONSHIPS ONLY AND DOES NOT REPRESENT ANY SPECIFIC MACHINE CYCLE
2. ALL MEASUREMENTS ARE REFERENCED TO 50% POINT OF THE WAVEFORMS
3. SHADED AREAS INDICATE "DON'T CARE" OR UNDEFINED STATE; MULTIPLE TRANSITIONS MAY OCCUR DURING THIS PERIOD

Fig. 2.4 RCA 1802 Timing diagram.

lines, used for transfering data between the memory, the μP and the I/O devices.

-TPA and TPB: Positive pulses that occur once in each machine cycle, TPA being first.

-Memory address lines : 8 multiplexed address lines. The higher order byte of a 16-bit memory address appears on the memory lines first at each machine cycle. The low order byte of the 16-bit address appears on the address lines afterwards, at the trailing edge of the pulse TPA.

-$\overline{\text{CLEAR}}$ and $\overline{\text{WAIT}}$: These 2 control lines provide 4 control modes as listed in the following truth table.

$\overline{\text{CLEAR}}$	$\overline{\text{WAIT}}$	Mode
L	L	Load
L	H	Reset
H	L	Pause
H	H	Run

As only two modes, reset and run, are used in the present application, there is need to provide a

control only to the $\overline{\text{CLEAR}}$ line, the $\overline{\text{WAIT}}$ line being in a high state. The circuit used for this operation is shown in fig. 2.5. (The circuits shown in this chapter are also shown in Appendix B.)

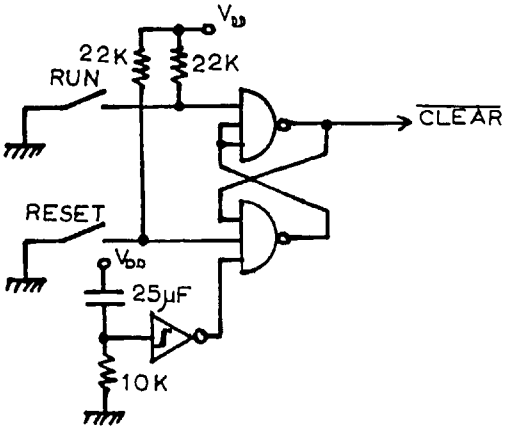


Fig. 2.5 μP Power on Reset-Run Circuit

-N lines : These lines are activated by I/O instructions. Those instructions are all of the 6N type, whith N = 1→9 for input and N = A→F for output. The 3 lines labelled N0, N1 and N2 correspond to the 3 LSB of N. In this application, because only 3 I/O ports are used, there is no need to decode these lines.

-Flags : These flags ($\overline{\text{EF1}}$, $\overline{\text{EF2}}$, $\overline{\text{EF3}}$ and $\overline{\text{EF4}}$) are inputs that transfer status information to the μP. Their levels can be tested by conditional branch instructions. Two flags, EF3 and EF4 are used in this case, EF3 for the printing controls and EF4 for further click generation.

-Q : Single bit O/P from the CPU that can be set or reset under program control and its status can be tested by conditional branch instructions.

-$\overline{\text{MWR}}$: A negative pulse appearing in a memory write cycle after the address lines have stabilized.

-$\overline{\text{MRD}}$: Its level indicates the direction of data transfer during an I/O instruction. A low level designates a memory read cycle.

2.3 Memory selection.

The total amount of memory used is 1K byte, of which 1/2K corresponds to an EPROM and another 1/2 K to RAMs.

-The IM 6654. This is an Intersil 4096-bit CMOS UV erasable PROM. The decision to use this device was taken because it was the only CMOS EPROM available with a 1/2 K capacity. RCA manufactures an EPROM of 1/4 K, therefore two of them would have been needed, increasing the cost of the final product. A problem arose while testing the program, it appeared as if the Intersil EPROM was not compatible

with the RCA μP. Looking at the IM 6654 timing diagram in fig. 2.6, it can be seen that the strobe pulse $\overline{E_1}$ should appear when the 9 address lines have stabilized and the μP does not naturally provide any signal at that time.

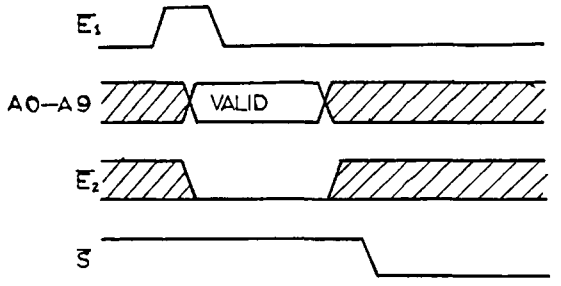


Fig.2.6 IM6654 Timing Diagram

Of the two available pulses, TPA appears too soon, when the memory address lines are still carrying the high order address byte and TPB appears too late , at the end of the cycle. In order to provide a suitable pulse, TPA was delayed by means of two Schmitt trigger inverter gates.

-The CDP 1822. This is a 256*4 bit static random access memory, which interfaces directly with the 1802 μP.

The memory mapping has been designed as follows:

03EF 0210	160*3 locations assigned to store data.
020C	00 or FF. Positive or negative click values
020B	Frequency mode
020A	Number of 1024 times mode.
0209	00
0208	Control data for O/P port N^{o} 2
0207	EEG data
0206	7F. Click baseline
0205	Click shape mode.
0204	00.
0203	4096 times control.
01FF 0000	Program

As the memory address lines are multiplexed it is necessary to latch the 8 higher order address bits which appear first. This is achieved by means of a CDP 1852, which is an 8-bit I/O port and can be used as a latch device, controlled by TPA. When the memory address lines are at the 8 lower address bits status, the 8 higher address bits are available at the output lines of the latching device. (fig.

2.7)

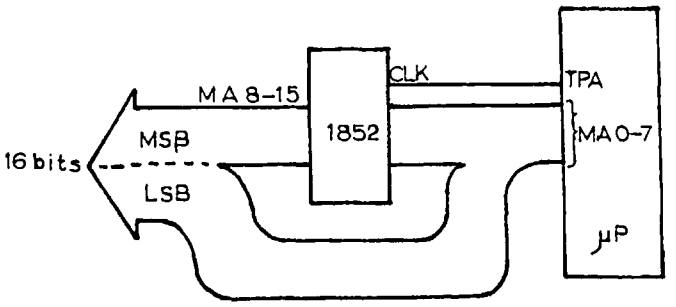


Fig.2.7 M.A. Latch Diagram.

Those 16 values should be decoded to achieve the memory selection. The addresses corresponding to each memory device are:

0000 ⎫
⎬ EPROM
01FF ⎭

0200 ⎫
⎬ RAM Pair 1
02FF ⎭

0300 ⎫
⎬ RAM Pair 2
03FF ⎭

What determines that a specific memory is selected is the 8 higher order address bits. From those the 4 MSB are always low. The 4 LSB are taken to a CD 4028 binary-dec decoder, whose truth table is:

Memory Address	O/P N^{o}
	0 1 2 3
0 0 0 0	1 0 0 0
0 0 0 1	0 1 0 0
0 0 1 0	0 0 1 0
0 0 1 1	0 0 0 1

As the IM6654 EPROM is selected by $\overline{S}$ going low and because the addresses for which that device should be selected are equivalent to lines 1 and 2 from the binary decoder being high, a NOR operation is performed to fulfil this condition. As this is a 512*8 bit device, a 9th memory address line should be provided. This line is taken from the LSB of the O/P of the latch device. As far the RAMs are concerned, each pair is selected by either line 3 or 4 from the 4013 binary decoder. No further logic is necessary as the RAMs are selected by $\overline{CS1}$ going high. The functional diagram of the memory system is shown in fig. 2.8.

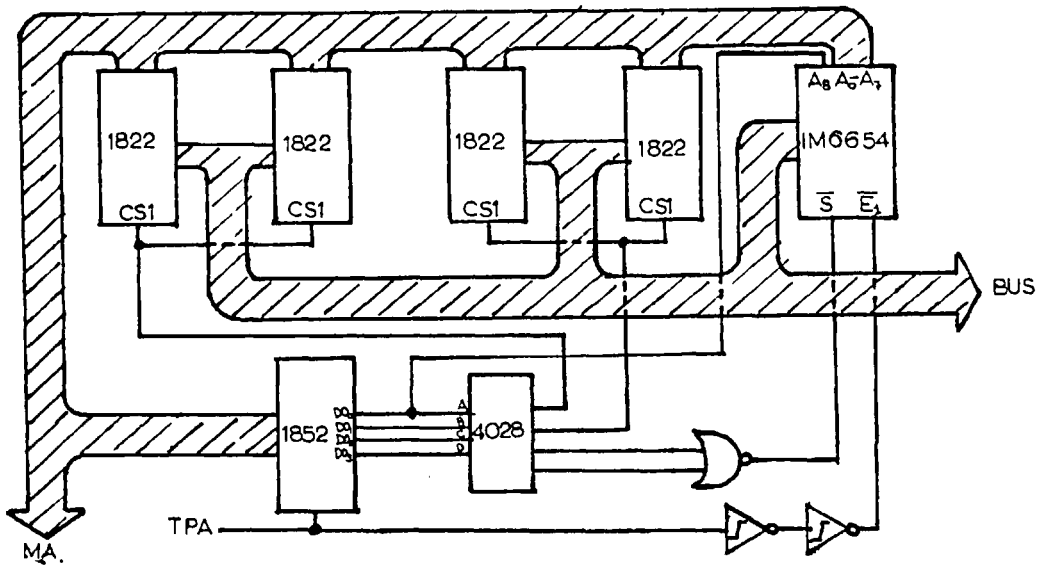


Fig.2.8 Memory System Diagram.

2.4 I/O Ports.

2.4.1 The CDP 1852.

The RCA CDP 1852 is a parallel, 8-bit, mode programable CMOS input/output port. It is compatible and interfaces directly with the CDP 1802 μP without additional components. The mode control is used to program the device as an I/P port (mode 0) or O/P port (mode 1). Three I/O ports are used in this application, one is programmed as an I/P port and the two others as O/P ports. Because of the I/O instructions used, N1 has been assigned to select the I/P port, N2 the O/P port N°1 and N0 the O/P port N°2.

	μP Instruction	N Lines		
		N2	N1	N0
O/P Port 2	61	0	0	1
I/P Port	6A	0	1	0
O/P Port 1	64	1	0	0

2.4.2 The I/P port.

Two different signals are supplied to the μP through the I/P port. One is the 8-bit signal from the AD converter and the second, a 4-bit signal from the external frequency and click shape switches. A 4019 quad AND-OR select gate is used to select the 4 LSB going into the input lines of the I/P port, as shown in fig. 2.9.

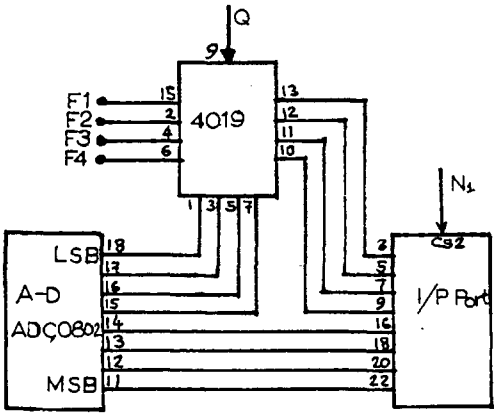


Fig. 2.9. Input Signals Selection.

The 4019 has 4 blocks of AND-OR select gate configuration. Selection is accomplished by applying Q and $\overline{Q}$ to the selection pins KA and KB as shown in fig. 2.10.

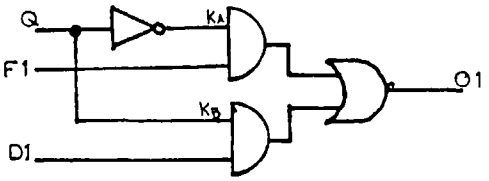


Fig.2.10. Individual 4019 Block.

The ADC 0802 is a CMOS 8-bit successive approximation A/D converter. Though it can be self clocked at a frequency set by means of an external RC, its clock is in fact derived from the 3.2 MHz crystal oscillator frequency by dividing it by a factor of 4, to give a clock of 800 KHz. In this way, the timing is more accurately established, this is critical as the converter is working at its maximun conversion rate. The converter is controlled by the $\overline{WR}$ pulse (fig. 2.11). When this signal makes a high to low transition, the conversion starts. Then, when the conversion is over, the $\overline{INTR}$ line makes a high to low transition.

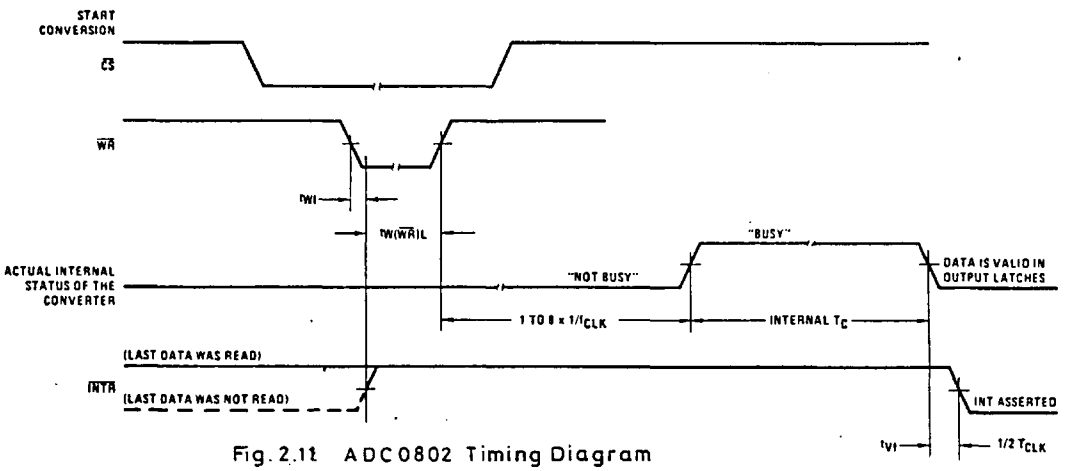


Fig.2.11 ADC0802 Timing Diagram

The inverted N1 signal, the particular N line activated by the I/P instruction used, is connected

to $\overline{WR}$. The $\overline{INTR}$ line goes to the clock of the I/P port (fig. 2.12). So, when the conversion is over, the execution of an I/P instruction will latch into the bus lines the data which is at the input lines of the I/P port and a new conversion will start.

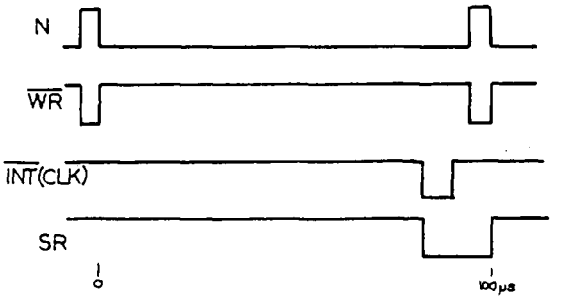


Fig. 2.12 A-D Converter Control Signals

2.4.3 Output port N^{o}1.

This O/P port is connected to the D/A converter, and is used to output first the clicks value and then the average response. The D/A converter is the ZN 425, 8-bit resolution, 1/2 LSB total error. The analog O/P , whose full scale value is 2.5 Volts, is buffered with a 741 operational amplifier in the configuration shown in fig. 2.13.

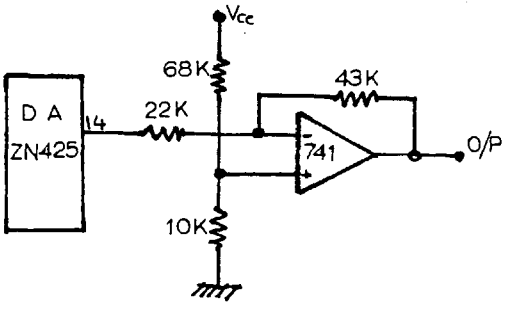


Fig. 2.13. D-A Buffer.

2.4.4 Output port Nº2.

This O/P port is used as a control device. It controls the 4066 quad switch, the pen recorder circuits, the three LEDs and provides the trigger signal for the oscilloscope.

Not Used	Trigg osc.	Quad sw.	Heater	Motor	L1	
21	19	17	15	10	8	Pin Number
0	0	0	0	0	0	Reset
0	0	0	0	0	0	Run
0	0(1)	1	0	0	1	Display
0	0	1	1	0	1	Heater ON
0	0	1	1	1	1	Print
0	0	1	0	1	1	Motor ON
0	0(1)	1	0	0	1	Display

This is the truth table of the O/P at the moment when 1024 clicks are generated. In the two other cases, 2048 and 4096 clicks, the only change will be the LED control, instead of being L1 the LED controlled will be L2 first and finally L3.

The 4066 quad bilateral switch has 4 individual bilateral blocks. (fig. 2.14). A pair is used to

gate to different circuits the signal coming from the D/A converter, one is the click signal, that goes to the click attenuator circuit; the other is the averaged response, which goes to the pen recorder circuits. The second pair is used to provide the two different signals being monitored by the oscilloscope, first, the EEG signal and later on, the averaged response. The two pairs are controlled by pins 15 and 17 from the O/P port Nº2.

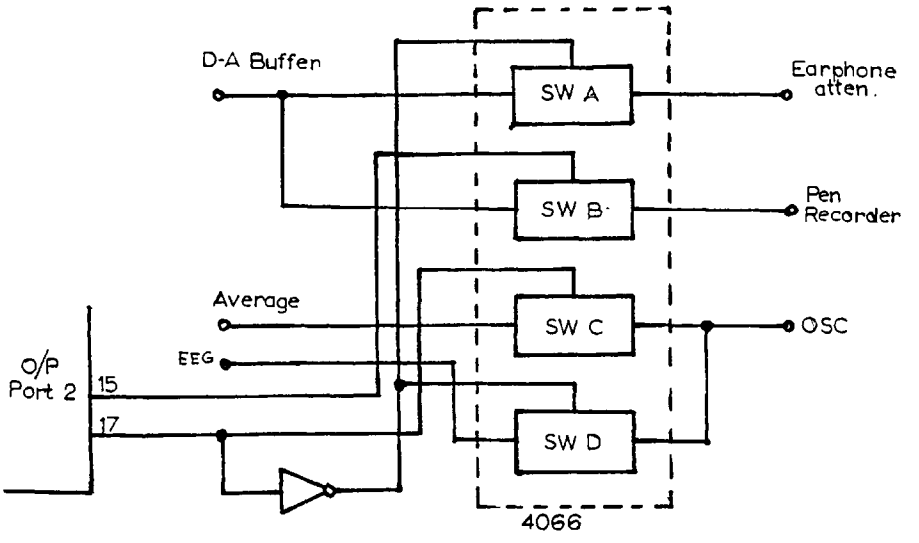


Fig. 2.14 4066 Quad Switch Diagram

2.5 Click generator.

The click generation is performed by the μP. Three different types of 100 μs width click sequences can be generated: positive, negative and alternate. Their correspondent digital values are shown in fig. 2.15.

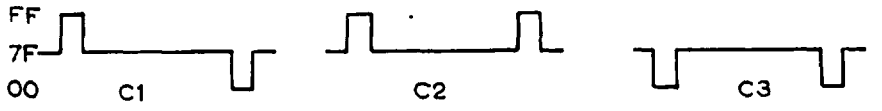


Fig.2.15 Clicks Generated.

The actual generation of each click shape can be roughly described as the process of outputing the contents of two memory locations, M1 and M2. The value stored in M1 is 7F, a value which corresponds to the baseline, and the value initially stored in M2 is FF, a value corresponding to the positive click. On the other hand, another memory location, M3, which contains one out of three values identifying a particular click shape is tested twice by the μP to keep or to change the value stored in M2. The first test is carried out before the generation of the first click. This test is done to inform the μP whether the value stored in M3 is C3 or not. If it is C3, the value in M2 is changed to 00, meaning that a negative click has been requested; if it is not C3, the value in M2 remains unchanged. Then, the first click is generated, data is read and averaged and just before the second click, and before any subsequent click, a new test is performed. This second test tells the μP whether the value stored in M3 is C1 or not. If not, the value in M2 remains unchanged and the following click is generated. If the value stored in M3 is C1, it means that the al-

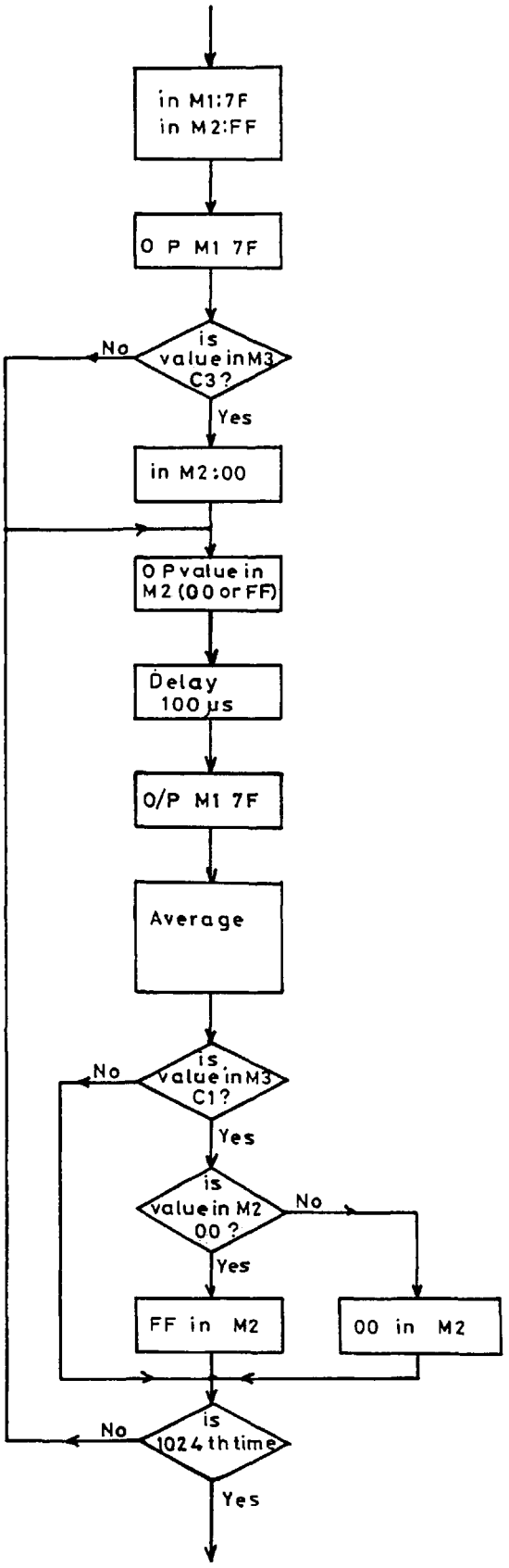


Fig. 2.16 Click Generator Flow Diagram

ternate click has been requested and therefore, the value in M2 is changed either from 00 to FF or from FF to 00. The click generator flow diagram is shown in fig. 2.16.

Two further stages follow, one of attenuation and a second of power amplification. Steps of 20 dB on the click sound pressure level are equivalent to a division or multiplication by a factor of 10 on the click amplitude. This is achieved with the circuit shown in fig. 2.17.

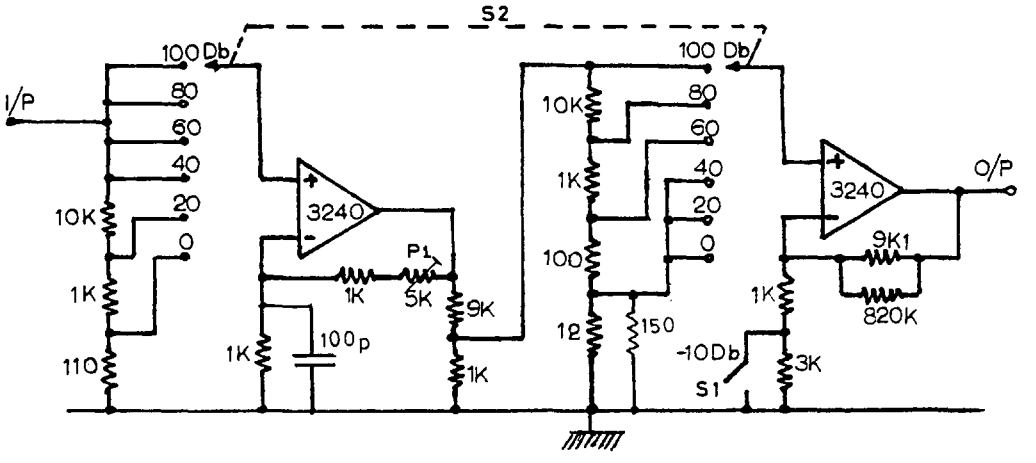


Fig. 2.17 Click Attenuator

Switch S1 allows reductions of 10 dB to the fixed values of 100, 80, 60, 40, 20 and 0 dB. Potentiometer P1 has external access, and its function is to provide the possibility of individual calibration of the click level. The design of the attenuator required special care to avoid the possibility of signal leakage since voltage reductions by a factor of 10^5 are needed. The circuit has been

built in a separated screened box, and the two attenuation stages are kept separated from each other.

The last stage of power amplification has been designed to provide at the 100 dB attenuator position, clicks of 5 Volts amplitude into the 10 Ohms load presented by the earphones. Fig. 2.18 shows the click amplifier circuit.

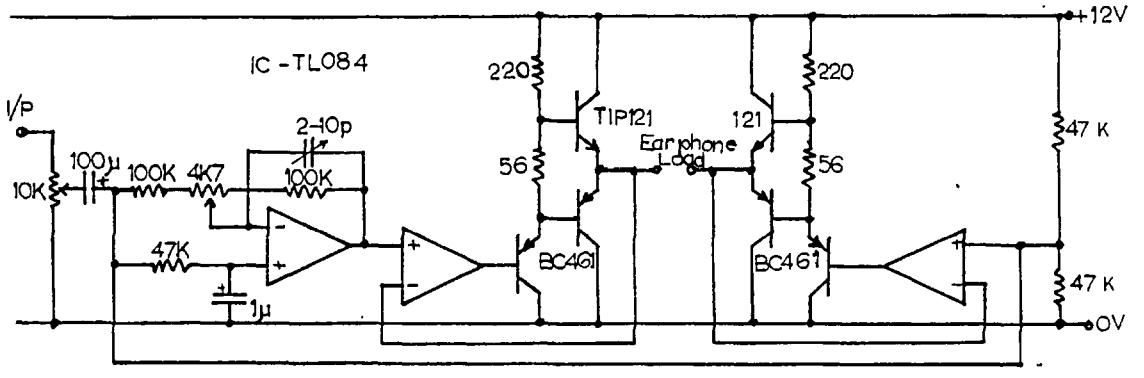


Fig. 2.18 Click Power Amplifier

Three different frequencies can be selected. On the prototype model, the frequencies were 20, 25 and 30 clicks per second, but for the second model this was changed to 10, 20 and 30 cps. The procedure to adjust the time between each click is a matter of three different delays, as shown in fig. 2.19.

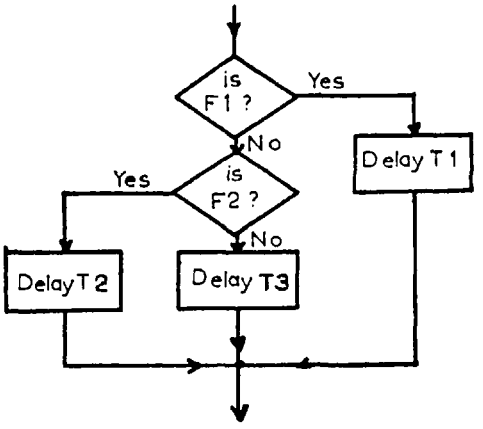


Fig. 2.19 . Original Click Frequency Flow Diagram.

This method, though successfull has the inconvenience of using a lot of memory locations, but this was not important when the first model was designed, as the length of the software could be fitted into the 1/2 K EPROM. But in the the second model the software was extended and its length exceeded the 1/2 K limit, so the program had to be optimized. By changing the delay routines some memory locations were saved. The new flow diagram is shown in fig. 2.20.

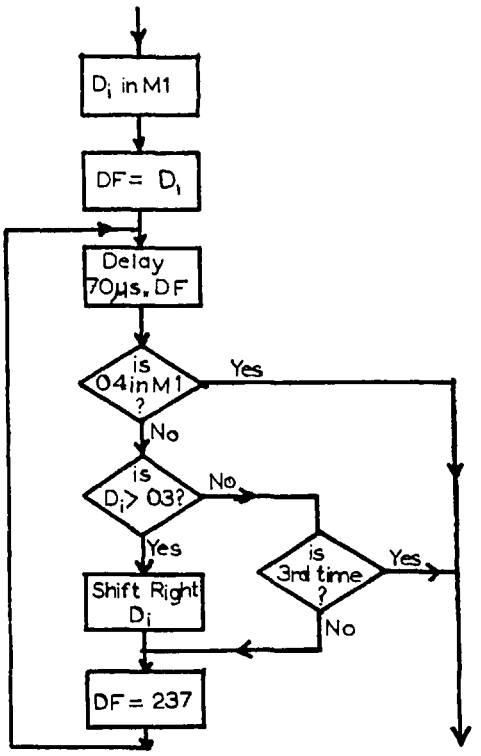


Fig. 2.20 Final Click Frequency Flow Diagram.

In this way, instead of using a different delay for each frequency value, the same delay is used for the three, and depending on the value of F chosen this delay is crossed 1, 2 or 3 times, and its length consequently adjusted. The values for the three different periods are:

T1=33.325 ms

T2=49.990 ms

T3=99.990 ms

2.6 The DC-DC converter.

As was mentioned before, the EEG measurements have to be taken with a circuit electrically isolated from the mains. To power the preamplifier stage, an isolated power supply is necessary. The principle used is to power a high frequency oscillator from the normal supply and apply these oscillations to the primary of a toroidal transformer, the secondary signal is then rectified and filtered to provide the positive, negative and ground lines. Because the frequency is high, the primary and secondary have relatively few turns, and can be wound on opposite sides of the toroid. This physical separation provide extremely good isolation and small capacitance between the two windings.

At the beginning, the circuit used was a self oscillator configuration, at a frequency of nearly 9 KHz, but this frequency proved to be too low since it created interference problems that could not be avoided even after screening the circuit; also, its sound could be heard as 9 KHz lies in the audible frequency range. It was decided then to increase the oscillation frequency well beyond 10KHz and to use another oscillator to power the amplifier. This has been done with a CD 4047, low power monostable/astable multivibrator. It is connected in the astable mode, and with the values of R and C

used , its output is at 48.8 KHz. This component has the advantage of providing two complementary O/P waves,which fulfills the needs of the circuit to provide positive and negative supplies.[22] The diagram is shown in fig. 2.21.

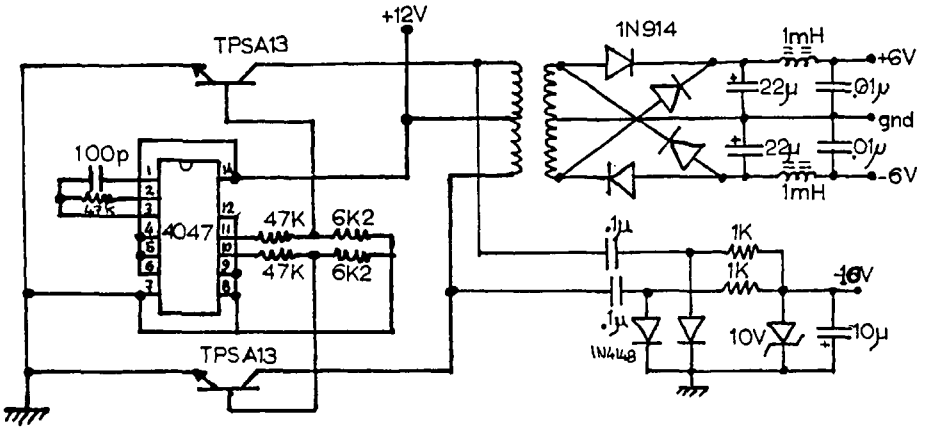


Fig.2.21 DC-DC Converter

2.7 The EEG amplifier.

The EEG amplifier comprises two stages, one electrically isolated from the mains providing a gain of $\simeq 2*10^5$ and a second non-isolated with a variable gain from 1 to 35.

The preamplifier consists first of a differential amplifier configuration; an instrumentation amplifier with a high CMRR is being used.[23] Then the signal is band filtered and amplified further in a second stage using an Operational amplifier mounted in a non inverting configuration. The amplified EEG

signal is then transferred to the non isolated circuits by optical couplers. Due to the non linear transfer characteristic of the opto coupler, some distortion is introduced by this signal transmission. To correct for the non linearity of the signal transfer a feedback should be supplied through a similarly non linear opto coupling path. For this reason two opto couplers are used as shown in the EEG amplifier diagram in fig. 2.22.

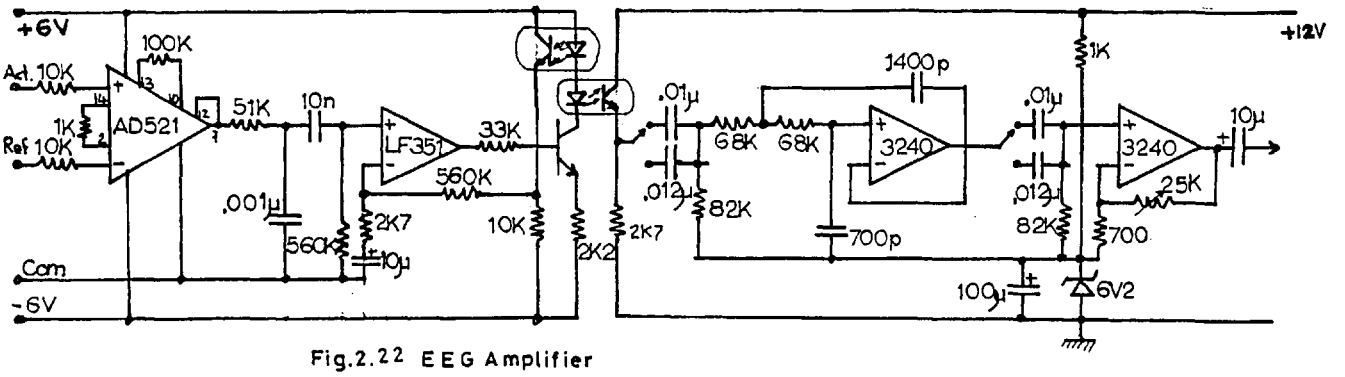


Fig.2.22 EEG Amplifier

Finally, the EEG signal is filtered and amplified by an externally controlled factor. Two first order filters are employed for the low cut-off frequency that can be set either at 30 Hz or at 250 Hz. An active 2nd order filter provides the high cut-off frequency at 2KHz. The filters Bode plot is shown in fig. 2.23.

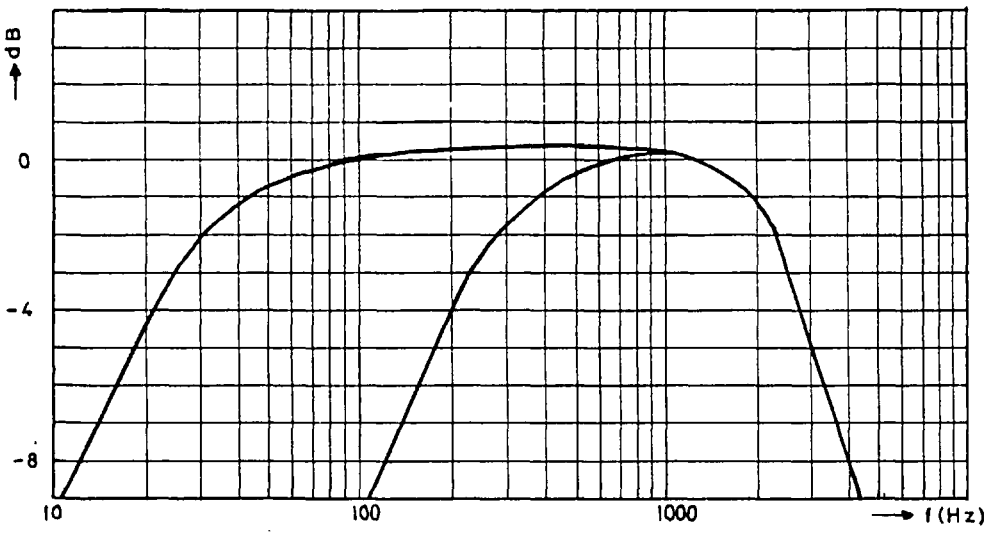


Fig.2.23 Filter Response

The amplified and filtered EEG signal response is fed to the AD converter, which samples it at a rate of 10 KHz; this value was suggested in the design guidelines and can be justified by means of the sampling theorem. As the converter handles signals from 0 to 5V, the EEG wave is AC coupled onto a 2.5V DC level to bias it in the middle of this range.

As has been explained, the extremely low S/N ratio of the EEG evoked response can be improved using the averaging technique. The average operation starts with the reading of a value digitized by the converter; the μP performs this by executing an I/P instruction, after which, the data is loaded into the accumulator. Let us call the three locations assigned to hold the result M1, M2 and M3. Using the ADD (add) and ADC (add with carry) in-

structions the successive additions are carried out; those two instructions use the register X as a pointer. First with X pointing to M1, an ADD instruction is executed, adding the contents of M1 to the value previously loaded into the accumulator. The result appears in the accumulator and if a carry is produced , the data flag is set. Then, two ADC instructions are executed, first with X pointing to M2, and then to M3. The results are again stored in M2 and M3 respectively. Before executing each ADC instruction the accumulator is cleared as that instruction adds the contents of the memory location pointed by X to the carry flag and to whatever value is stored in the accumulator. The operation described is shown diagramatically in fig 2.24.

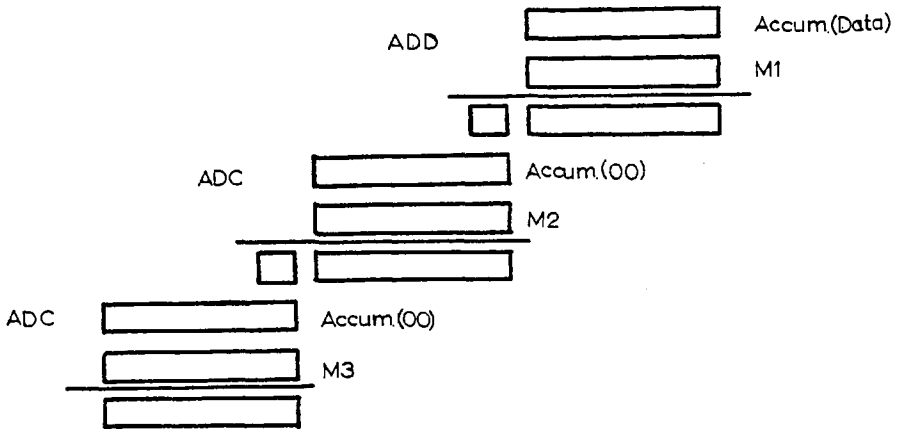


Fig.2.24 Adding Operation Diagram

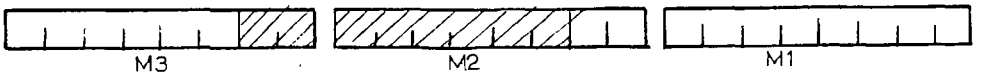
This operation is repeated 160 times after each click, giving, at a sampling rate of 10 KHz, 16 ms of readings starting at the trailing edge of the click. The average routine was tested using as an

input signal a click controlled delayed pulse. The input signal and the averaged response are shown in fig. 2.25.

2.8 Average response display.

After having added 1024 responses, the next problem to solve was to decide which 8-bits, out of 24 were the more likely to contain the information wanted.

At first it was thought that because 1024 values had been added, if the average of those 1024 values had to be performed, it should had been necessary to display the 2 LSBs of M3 and the 6 MSBs of M2, as shown below.



But the result so obtained was not useful because it had a large DC value and the peaks were too tiny to allow easy recognision ; therefore, it was decided to look for a bigger signal by taking into account the bits of less weight, that is to perform a shifting of the 8-bit long window towards the right; this yielded an improvement in the signal, and doing it this way, some tests were carried out

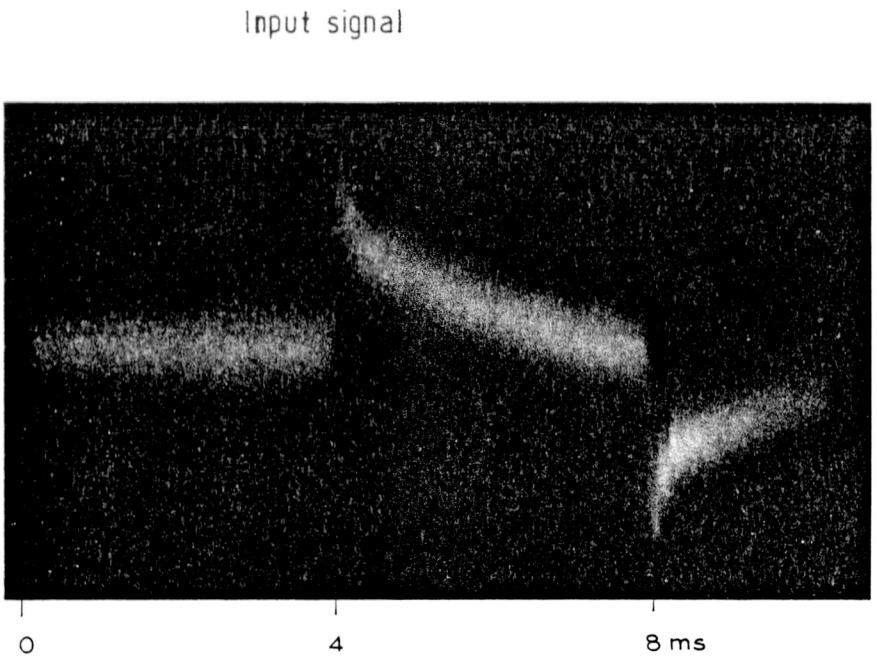
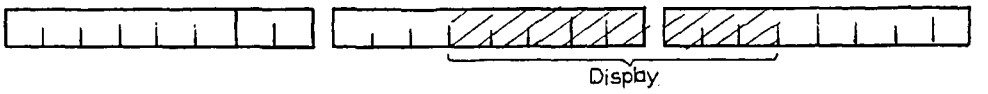
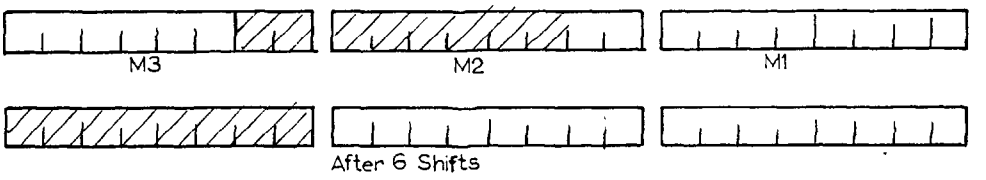


Fig. 2.25 Test of average routine.

to find out which bits were able to provide a good response. The result was the 5 LSBs of M2 and the 3 MSBs of M1, so those were usually displayed.



But this method had many limitations regarding the input signal. It assumed the EEG signal to be in the same range for all subjects, and that the amplification settings were constant. Neither of which is true. Therefore, it was necessary to develop a new approach to place the 8-bit window in the optimun position to give maximun output in each case. Let us call M1(i), M2(i) and M3(i) the three locations where the data corresponding to the ith poststimulus sampled point is stored. M3(i) was chosen as the locations to be displayed, so all the tests are done to the values stored in them. As was said before, after adding 1024 responses, the data could go as far as the 2 LSB of M3(i), therefore, the first thing to be done is to fill the M3(i) locations with data from M2(i), by shifting towards the left the appropriate number of bits.



The real obstacle to get a recognisable aver-

aged evoked response is in fact the existence of a DC value, which is not significant regarding the shape of the response.This DC value is originated in the manner the EEG is fed to the A-D converter. As was said, the EEG signal has an added 2.5 V, which is digitized and added 1024 times, and is equivalent to either 0 or 1 at the MSB of all the M3(i) locations, so a search routine was designed to compare the MSB of M3(1) with the other 159. If all are the same, indicating either zero or a DC level, a ring shift left is performed on all the M3, M2, M1 locations and again the new MSBs are tested as before. When it is found that the MSB of M3(1) differs from the MSB of any of the other M3 locations, that means that the signal contribution now starts from the MSB position and the maximum number of shifts have been done in order to allow the 160 M3 locations to hold the optimal signal to be displayed. This was called the "Auto search" procedure.

What is actually done is first to store in memory the MSB of M3(1), to which the MSB of M3(2) is added, and the result is tested; if it is 0, it means that the MSBs of M3(1) and M3(2) are the same, independently of it being either 0 or 1; in this case, the MSBs of the other M3 locations are tested in a similar manner. When the 160 locations have

been tested and it is found that all their MSBs are the same, a counter is incremented and a ring shift left of the 160 M3-M2-M1 locations is performed. The reason for having this counter where a record of the number of shiftings is kept, is that it exists the possibility of adding further 1024 responses, so before this is started, the data is put back into its original place, by performing as many ring shifts left as shifts right were done, plus 6.

After some tests were carried out using the auto search routine for different stimulus levels a problem arose when 100 dB SL was applied to the subject. This high level provokes interferences that are picked up by the EEG preamplifier. This interference has the shape of a transient ocurring in the first ms after the trailing edge of the click. The consequence of this is that a peak which is not a BSER component is averaged and when the search for maximum values in memory is performed, that peak is taken as the largest one, without considering the real BSER components. To solve this it was decided to apply the search routine only beyond a point equivalent to 1 ms after the trailing edge of the click.

When the searching operation is over, the value stored in the M3(i) locations is, by means of an I/P instruction put into the D-A converter and the averaged signal can be visualized, if oscilloscope facilities are available; a synchronisation signal is provided for that purpose. Since a display over 16 ms is desired, the time each value remains on the output is adjusted to achieve that. The μP stays displaying the signal and at the same time, it tests the status of the EF3 flag, which is normally high; when the operator requests for a printing of the averaged response, this flag changes status and the μP initiates the printing process which involves the generation of control signals for the pen recorder circuits. This has been referred to at the part concerning the O/P port N°2. Two signals are designed to first, switch on the stylus heater, and then after a delay of $\simeq$ 7 sec, start the motor, whose speed is controlled by means of a voltage regulator. It was necesary to low pass filter the signal to be displayed or printed as part of the reconstitution process from the samples, to obtain a recognisable response. At the display time the EF4 flag is continuously tested to know whether or not another 1024 responses (or 2048) have to be added. This is obviously done when the limit of 4096 responses added (L3 on) has not yet been reached.

2.9 Results.

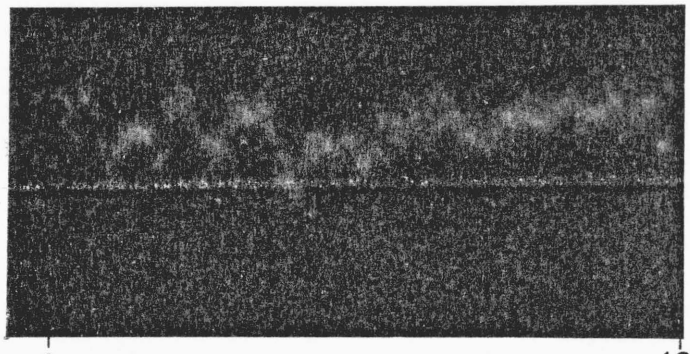
Some of the typical results obtained with the BSER Audiometer are displayed over the next pages, to give an idea of their usual appearance.

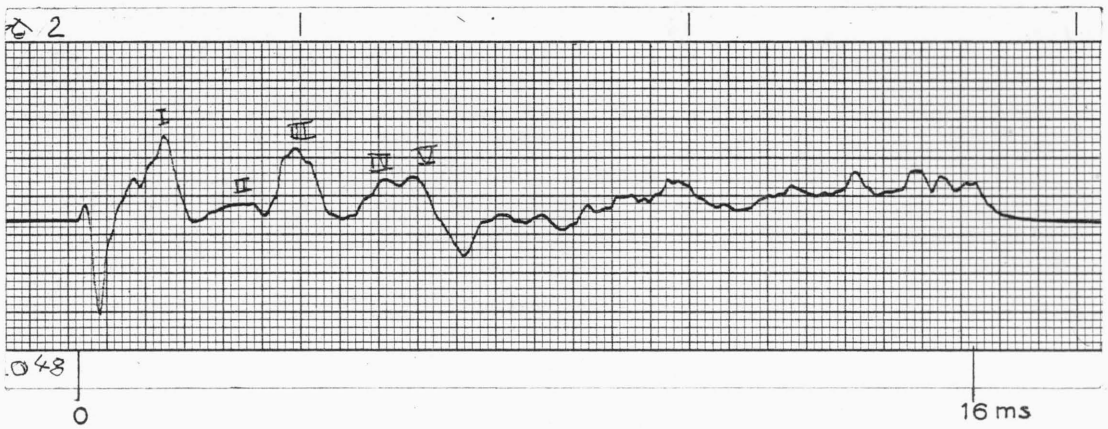
Figure 2.26 shows the two possibilities of obtaining the response, either visualizing it, or printing it using the pen recorder. The responses were obtained from a subject with normal hearing, using alternate clicks at 80 dB SPL at a repetition rate of 30cps. The lower cut-off frequency used on the EEG signal was 250 Hz; 1024 responses were added for the first case and 2048 for the second one.

Figure 2.27 shows a comparative display of the results obtained when 1024, 2048 and 4096 responses are added. The settings are similar to the those described above.

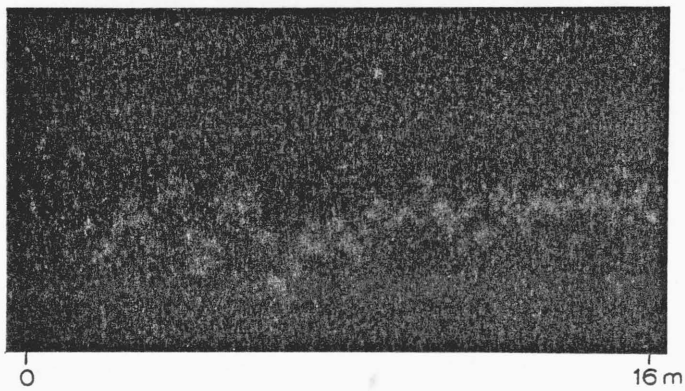
Figure 2.28 shows the external appearance of the BSER Audiometer and the EEG preamplifier.

Case 1: 1024 Responses added





Case 2: 2048 Responses added



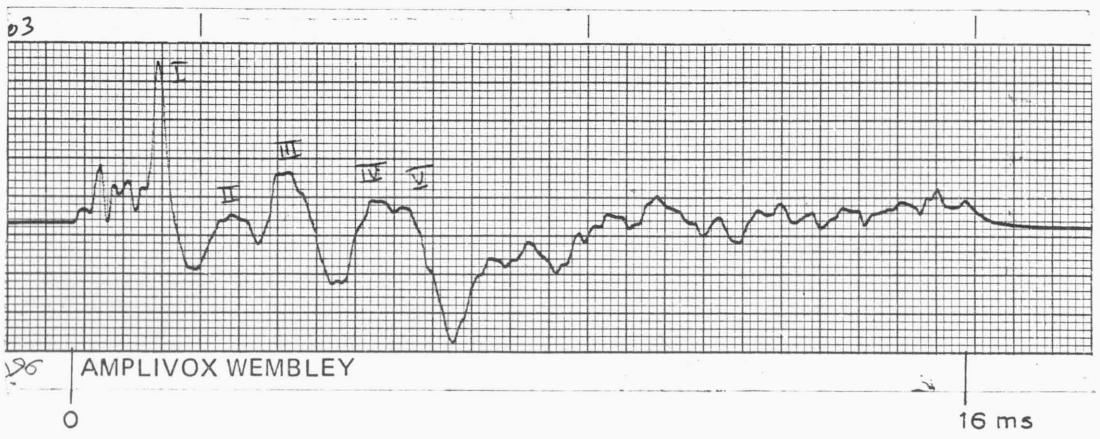


Fig. 2.26 Typical results

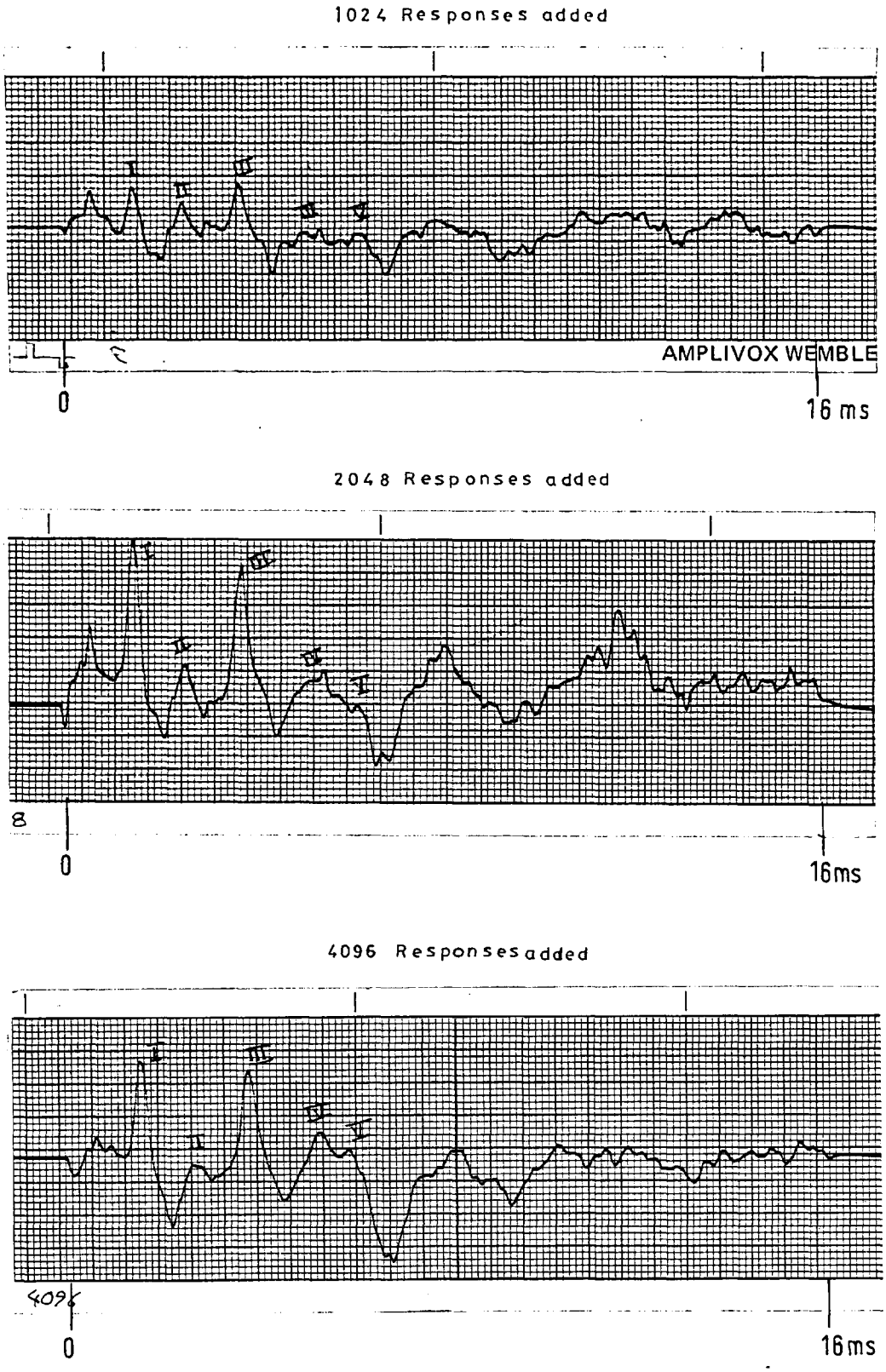
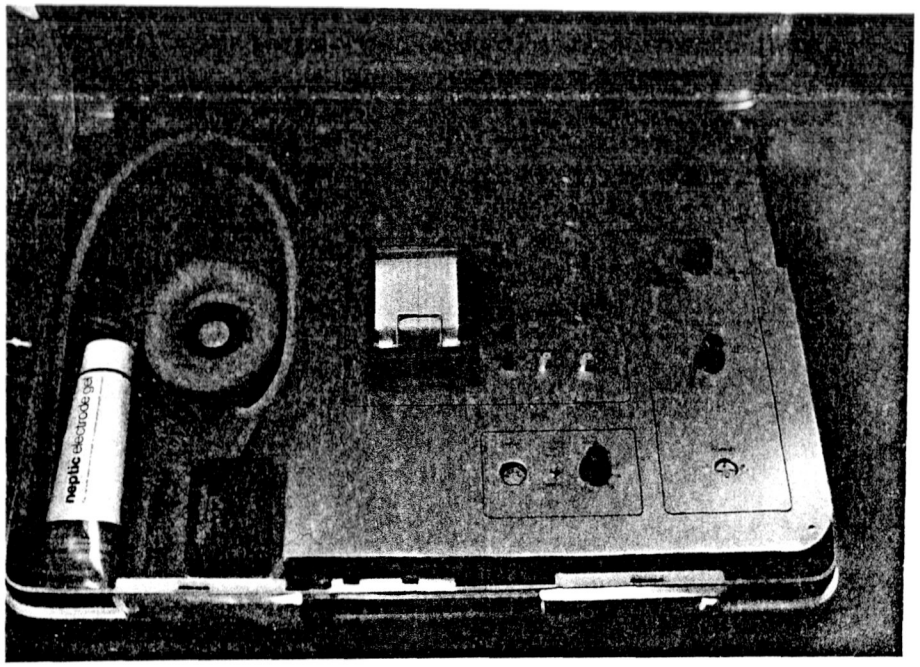


Fig. 2.27 Averages of 1024, 2048 and 4096 responses.



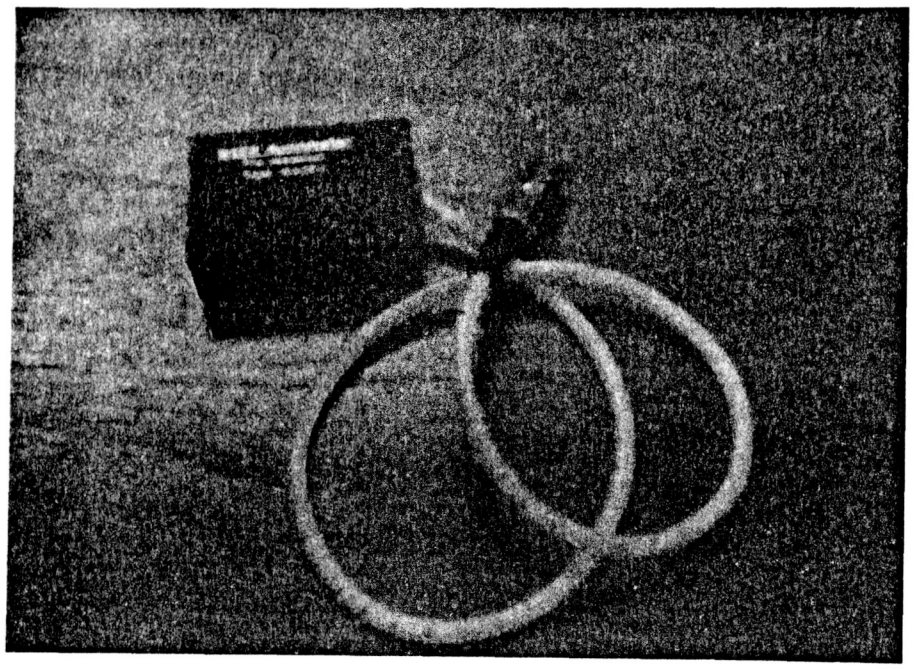


Fig. 2.28 BSER Audiometer and preamplifier.

CHAPTER 3

CORRELATION ANALYSIS OF AUDITORY BSER

3.1 Introduction.

Some subjectivity is unavoidable when the auditory BSER are visually analysed. To reduce its effect other methods have been developed, based on the pattern of the response, which aim to produce objective results perhaps with an assigned statistical significance. One approach used consists in detecting the presence of a pattern in members of an ensemble of poststimulus EEG records by forming the ensemble correlation coefficient between individual records and a reference.[24] The reference used might be the overall average response to a determined high level stimulus, but this has the disadvantage that the pattern of an adequate response does change with stimulus level because of the changing latencies of different components, so the correlation method may be deteriorated by this effect.

It was required therefore to carry out a correlation analysis using as a reference pattern a

1024 point average corresponding to different stimulus levels, and compare the sensitivities so obtained. EEG records corresponding to different stimulus levels were divided in groups of 32 responses and their respective coherent averages (subaverages) calculated. The 1024 ensemble average was also calculated. Then, ensembles correlation coefficients of the 32 subaverages against the 1024 point average corresponding to

a) a higher stimulus level, and

b) the same stimulus level,

were formed per each stimulus level.

3.2 Recording Method.

The EEG data and the stimulus mark were recorded simultaneously on different channels of a magnetic tape. The EEG response was previously band filtered at a lower cut-off frequency of 250 Hz and high cut-off frequency of 3.2 KHz. The stimulus rate used was 20 per second, at a levels of 80, 60, 40 and 20 dB. above the threshold of hearing (Not all the cases were analyzed at 20 dB.). These two signals were subsequently digitised with 11-bit precision using an IBM 1800 com-

puter. The corresponding digital values were stored by blocks of 1200 words on a tape, with the two channels alternating between blocks. The digitisation rate used was 6 KHz, which means that there were 300 sampling points after each stimulus. Since most of the important components of the BSER appear in the first 6 ms, it was decided to truncate the 300 sampling points to 64, which is equivalent to ≃10 ms of record. The first step after the digitisation is the separation of the two channels, then the stimulus should be localized rather accurately to be able to perform the next step which is the averaging process.

Some difficulties arose in searching for the click mark. Its digital value was variable and also, it was not always recognisable at all. This was due to the fact that the click that had been recorded was the same signal appearing across the earphones, which is in fact a transient lasting about 100 μs, too short to guarantee a sampled point over that interval. Some time was spent developing software able to identify the point where the click was supposed to appear, but another method was tried later that proved more efficient. The short click recorded on the analog tape was used to trigger a monostable circuit designed to

provide a longer output pulse to be used in the digitisation instead of the original one with the advantage of assuring a sampled point easy to detect by software means. The circuit is shown in fig. 3.1.

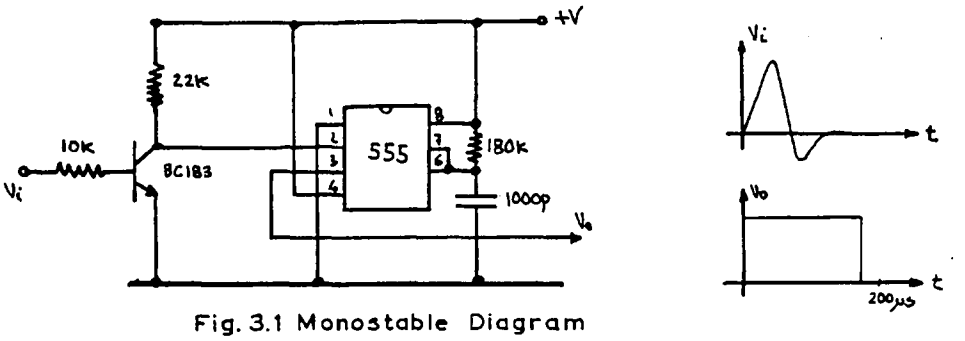


Fig. 3.1 Monostable Diagram

Software was developed then to localise the clicks, read 64 EEG data values starting at the one corresponding to the click, and perform the averages; 32 of 32 responses each and the 1024 point average. The 33 resulting averages constitute each a block, which are stored on a magnetic tape. The flow diagram is shown in figure 3.2.

3.3 Correlation Coefficient Analysis.

The correlation coefficients were calculated using the expression:

$$p = \frac{\sigma_{xy}}{\sigma_x \cdot \sigma_y}$$

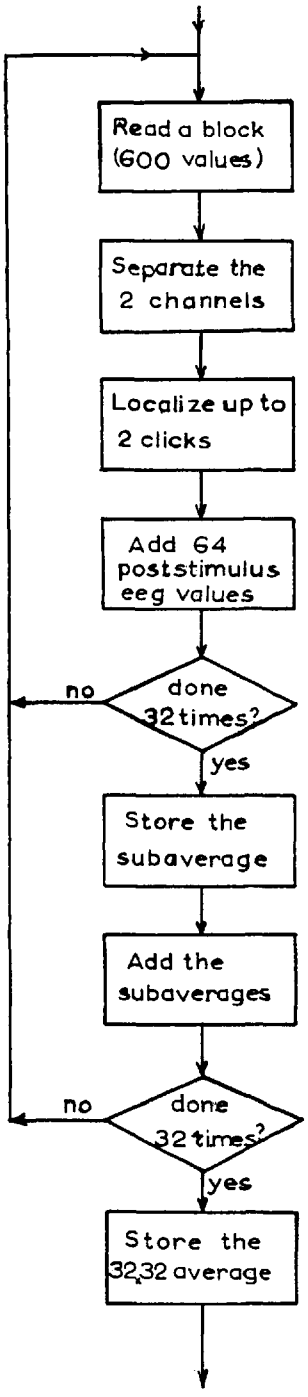


Fig. 3.2 Coherent Average Flow Diagram

where x and y are the two variables studied with $\bar{x}$, $\bar{y}$ being their respective means. σ_x^2 is called the variance, defined as,

$$\sigma_x^2 = \sum_{i=1}^{N} \frac{(x_i - \bar{x})^2}{N}$$

and σ_{xy} the covariance, defined as,

$$\sigma_{xy} = \sum_{i=1}^{N} \frac{(x_i - \bar{x})(y_i - \bar{y})}{N}$$

σ is called standard deviation, and σ / N the standard error. The correlation coefficient is interpreted as a measure of association between two quantitative variables. The standard deviation, also known as a root mean square (rms) is frequently used as a measure of variability.[25]

Software was developed to carry out the necessary calculations and bring forth the 32 correlation coefficients per stimulus level and rank order them according to algebraic magnitude with the aim of clarifying the effect of changing the stimulus level, on the grounds that the original order of correlation coefficients is apparently random. The software flow diagram is shown in figure 3.3.

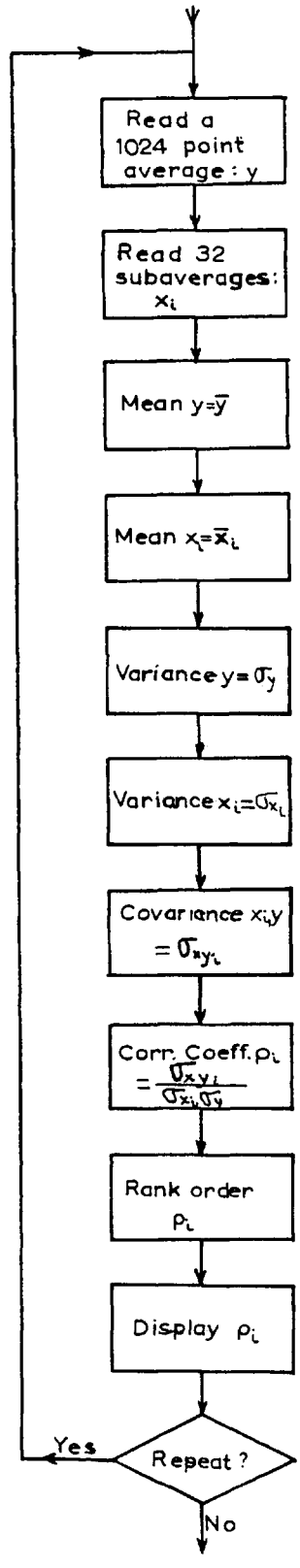


Fig.3.3 Correlation Coefficient Flow Diagram

3.4 Results and Conclusions.

Data from 9 subjects were analysed as described. The results are displayed on the following pages, separated into three cases, where,

case a) Correlation coefficients of the 32 subaverages responses to:

□ 80 dB

○ 60 dB

△ 40 dB

\+ 20 dB

stimulus level against the 1024 average response to 80 dB stimulus level.

case b) Correlation coefficients of the 32 subaverages responses to:

□ 80 dB

○ 60 dB

△ 40 dB

\+ 20 dB

stimulus level against the 1024 average response to 80, 60, 40 and 20 dB stimulus level respectively.

case c)

c.1 Correlation coefficient of the 32 subaverages response to 60 dB stimulus level against the 1024 average response to:

□ 60 dB

○ 80 dB stimulus level.

c.2 Correlation coefficients of the 32 subaverages response to 40 dB stimulus level against the 1024 average response to:

□ 40 dB

○ 60 dB

△ 80 dB stimulus level.

c.3 Correlation coefficients of the 32 subaverages response to 20 dB stimulus level against the 1024 average response to:

□ 20 dB

○ 40 dB

△ 60 dB

+ 80 dB stimulus level.

The mean correlation coefficient and standard error values corresponding to each of the cases studied are summarized on a table at the end of this chapter. Also the histograms of each ensemble correlation coefficient have been plotted.

As far the cases a) are concerned it is observed, specially on subjects labelled A, C, D and H that the curves are displaced towards lower correlation values when the stimulus level of the

subaverages response studied decreases. This has been described before (R. McLelland[26], 1978), and is attributed to the increase of peak latencies of the evoked response when the stimulus level is decreased; this is equivalent to a decrease on the mean correlation coefficients as can be observed on table 3.1. Less consistent variations are reported when the stimulus level of the reference pattern used is the same as the one corresponding to the subaverages analysed. On the table 3.1 it can be observed that when the stimulus level of the reference pattern is increased, starting at the one corresponding to the subaverages analysed, up to the highest stimulus level, a reduction on the mean correlation coefficient is reported, effect equivalent to a shift towards lower values of their respective curves.

The observations described suggest that, in general, some improvement in the sensitivity is indeed obtained when other stimulus level averages than the highest available is used as a reference pattern. The analysis of data from more subjects, including some hearing abnormalities, would be desirable in order to support the tentative conclusion stated above. Also the analysis of unstimulated EEG would provide the basis for the determi-

nation of the non response condition.

The results shown in the following pages have been separated according to subjects. The rank correlation coefficients have been plotted using as abscissa the re-ordered sweep Kl and the values of the coefficients as ordinate.

Regarding the histograms, the abscissa corresponds to intervals, 0.2 width, of the correlation coefficients from -1.0 to +1.0. The ordinate f corresponds to the number of occurrences of the correlation coefficients between each interval.

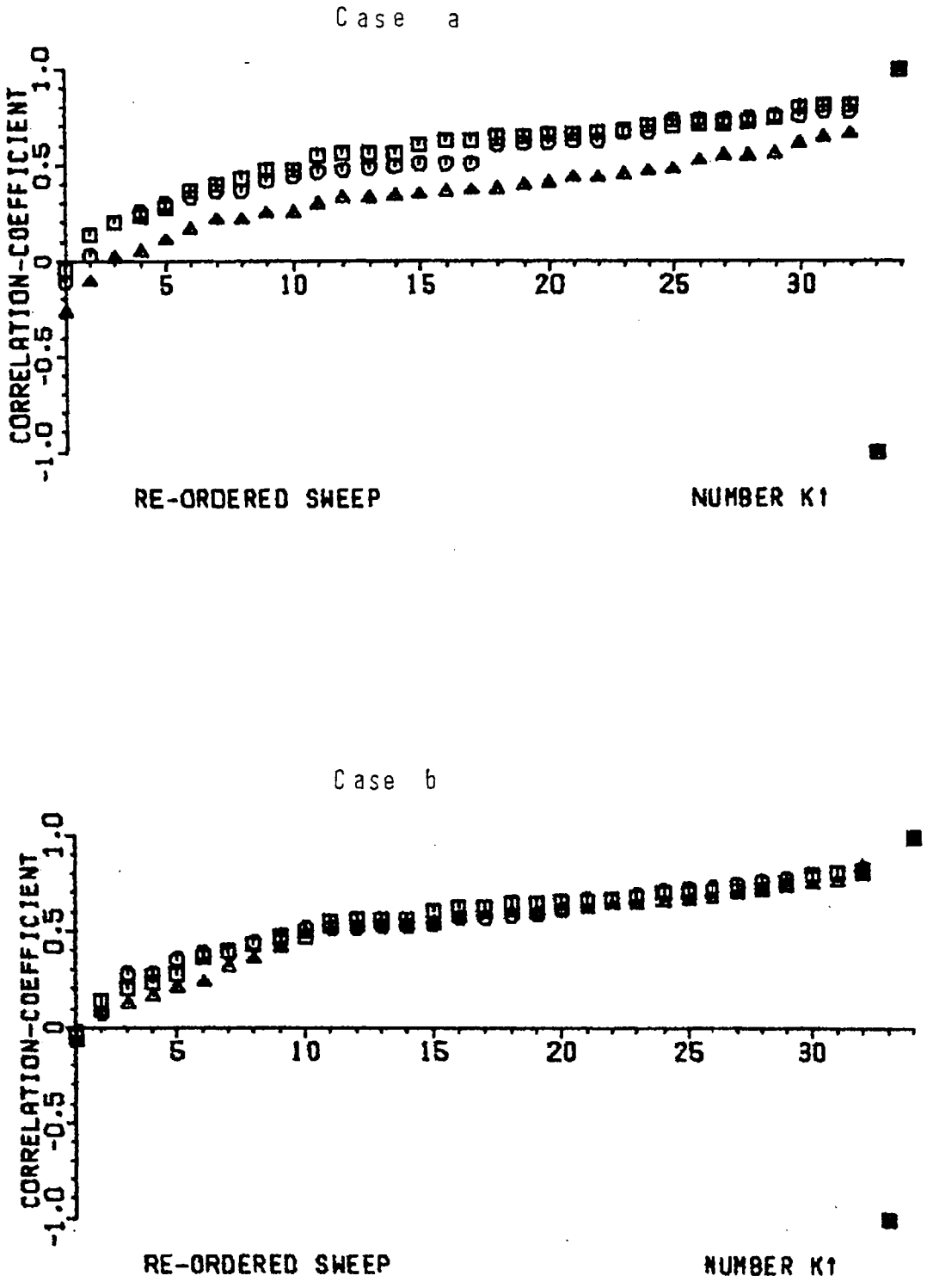
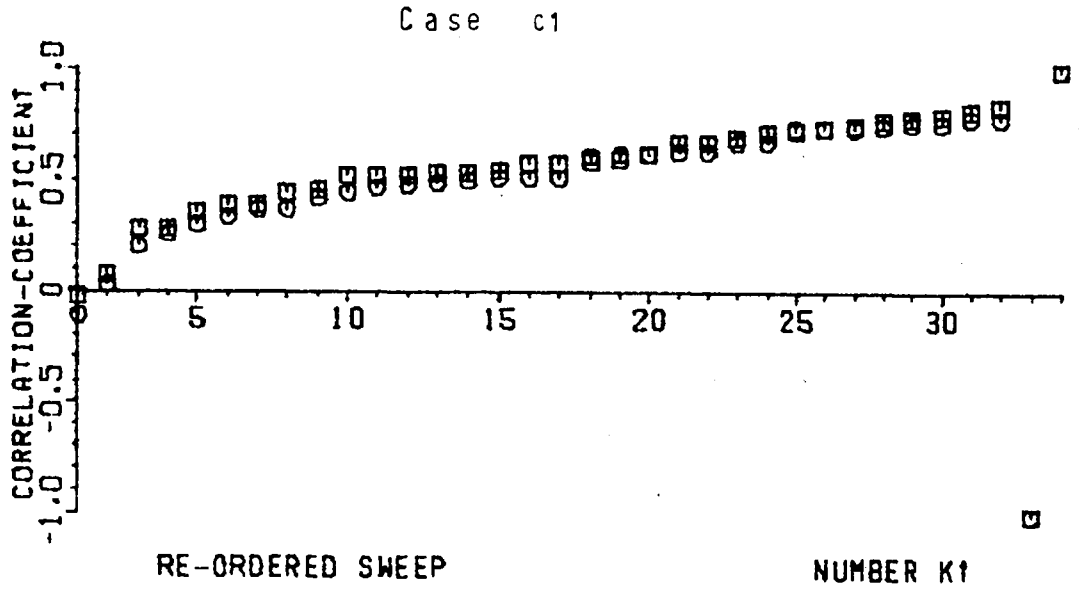


Fig. 3.4 Subject A - Cases a and b.



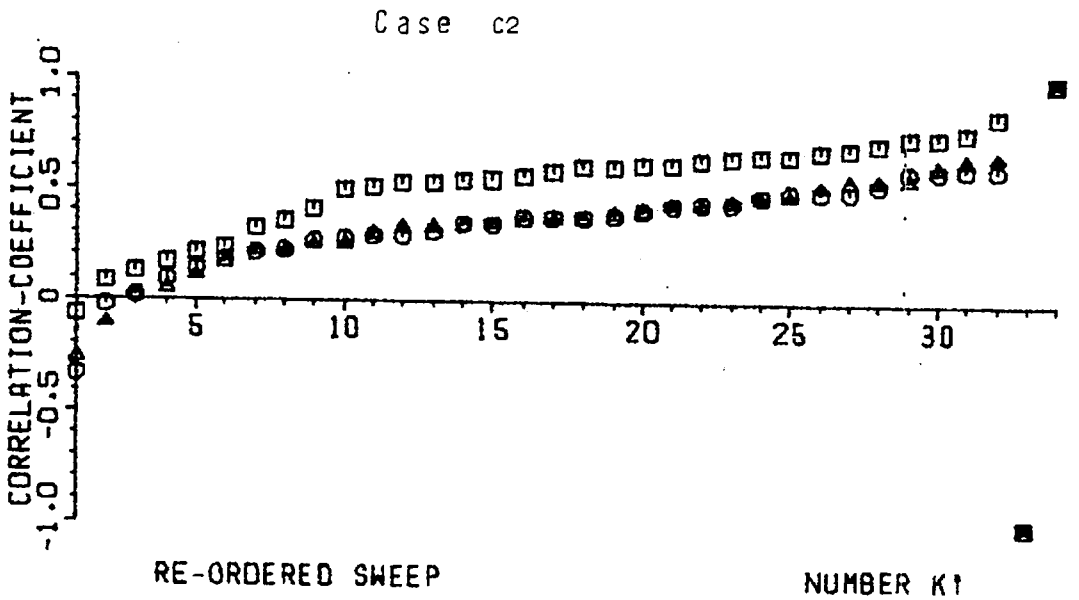


Fig. 3.5 Subject A - Case c.

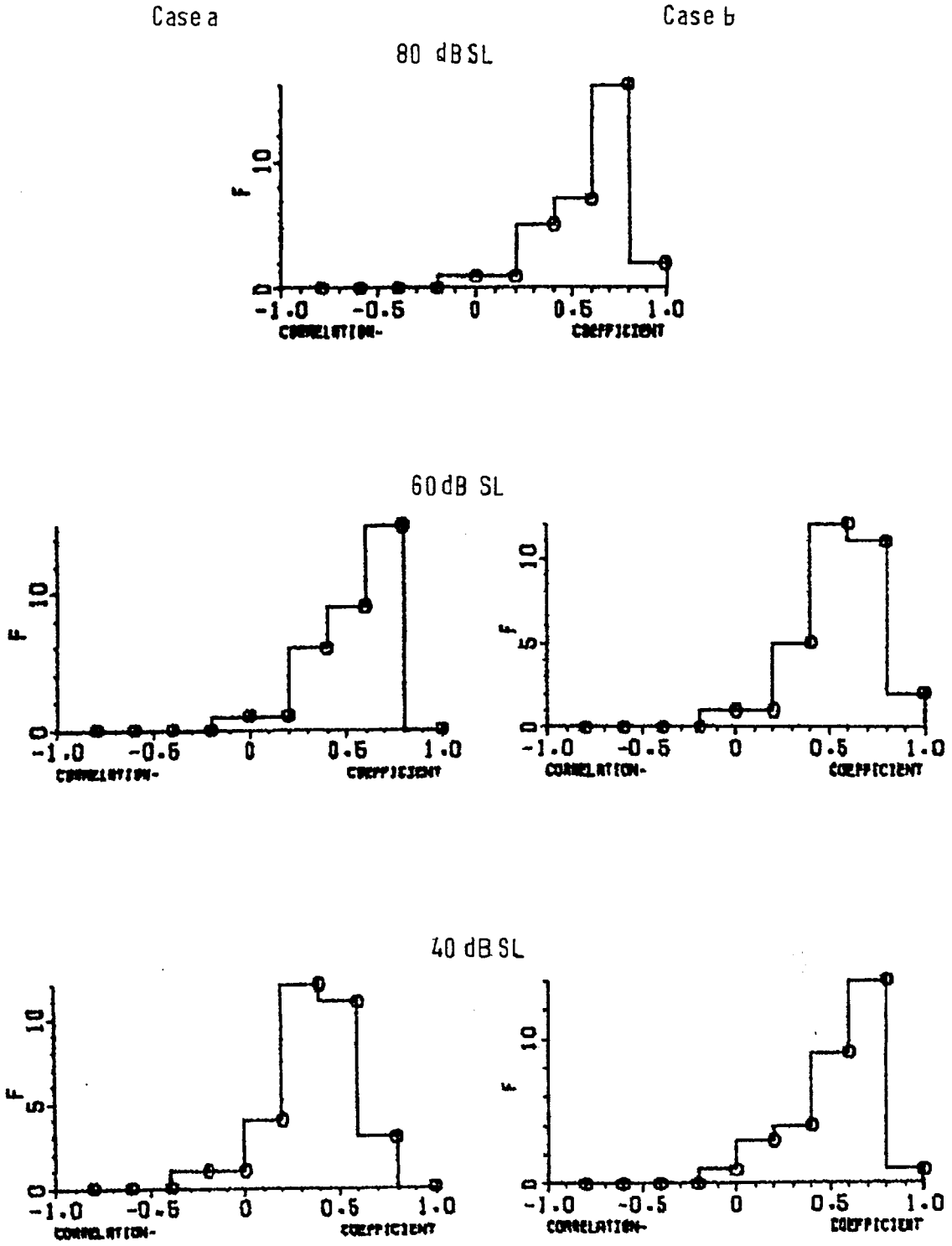
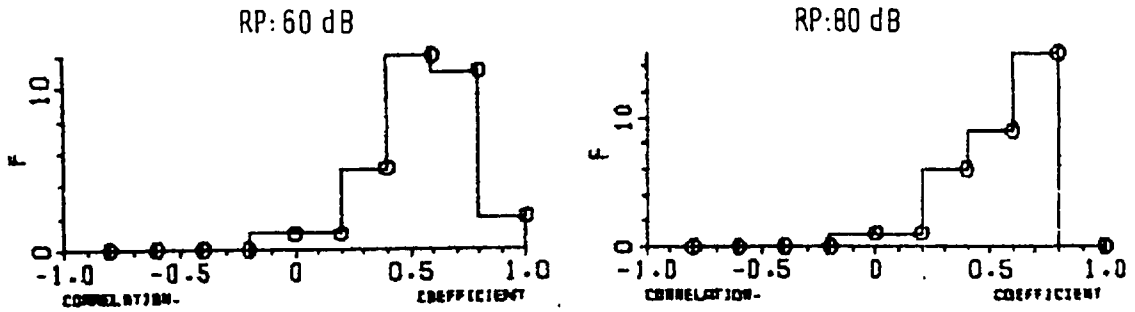


Fig. 3.6 Subject A - Cases a and b histograms.

Case c1



Case c2

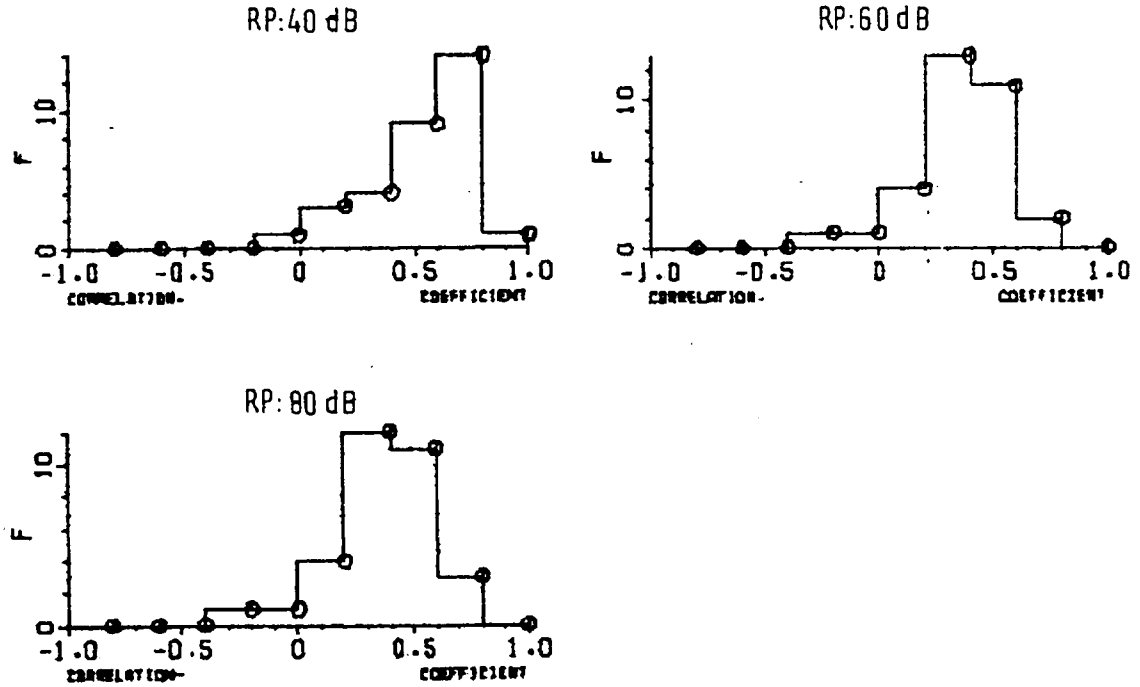
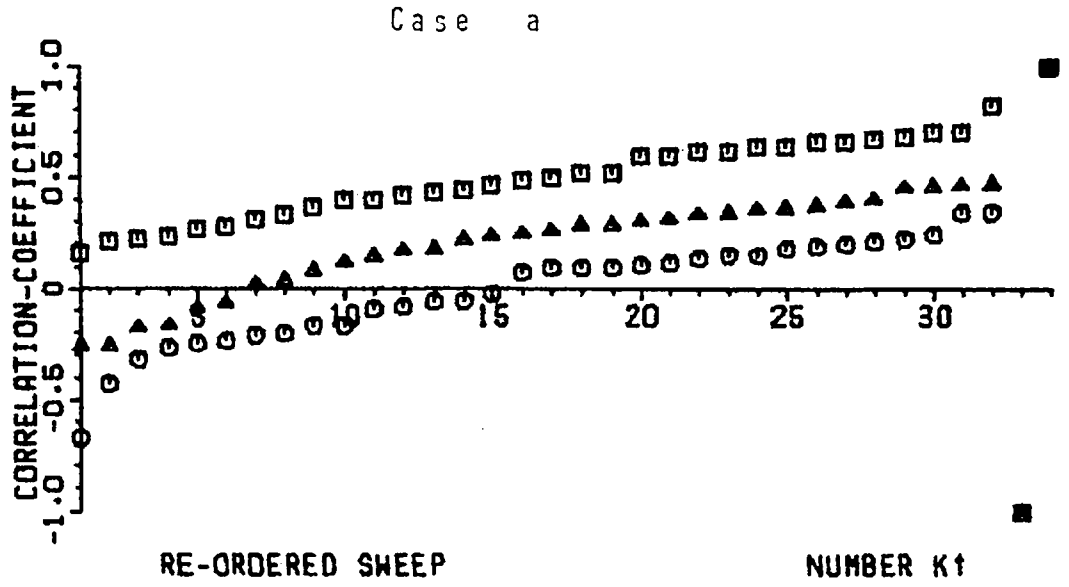


Fig. 3.7 Subject A - Case c histograms.



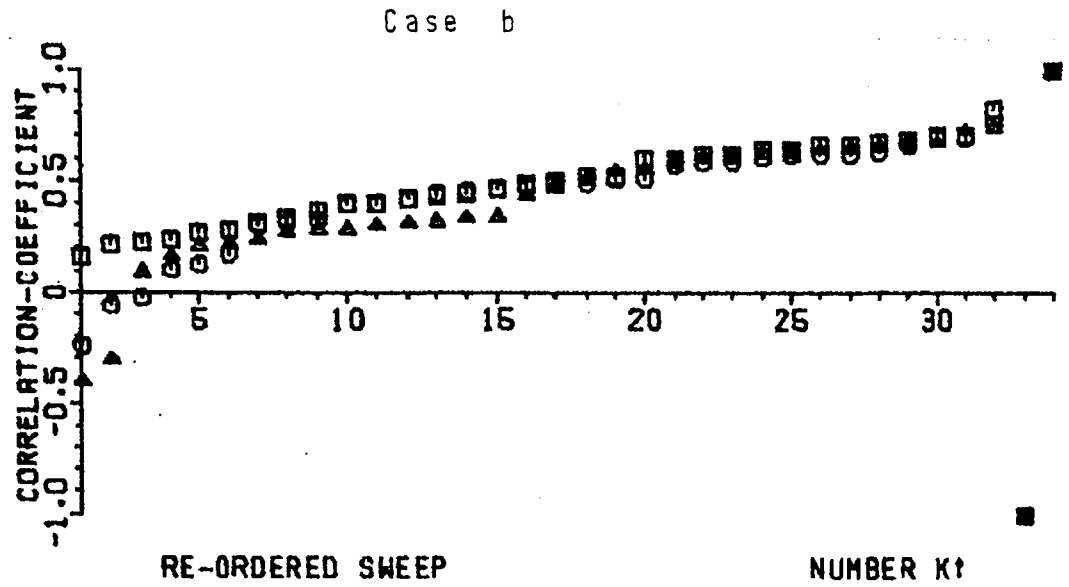
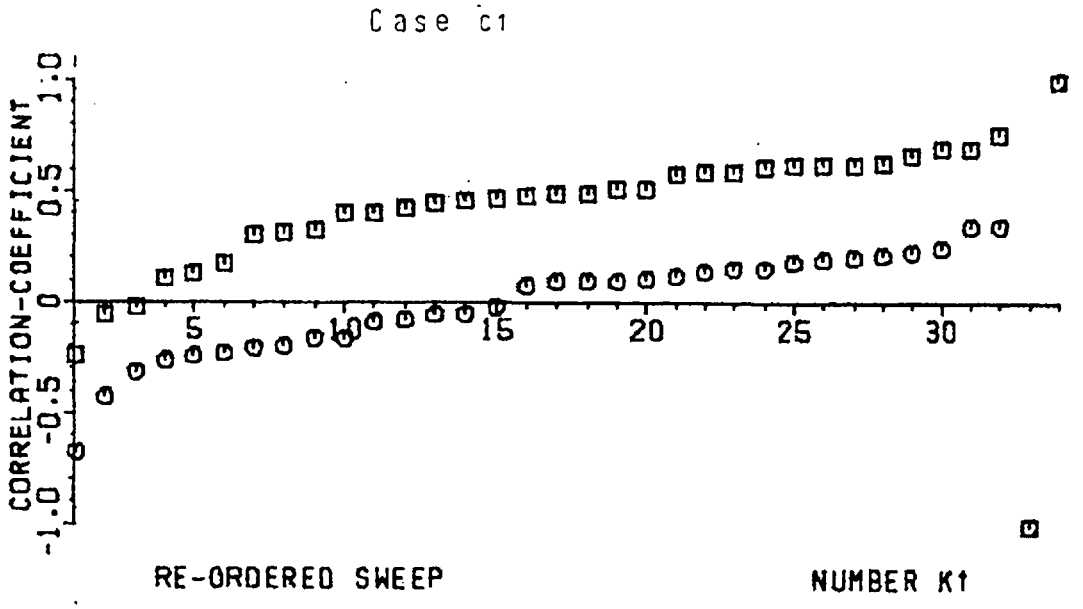


Fig. 3.8 Subject B - Cases a and b.



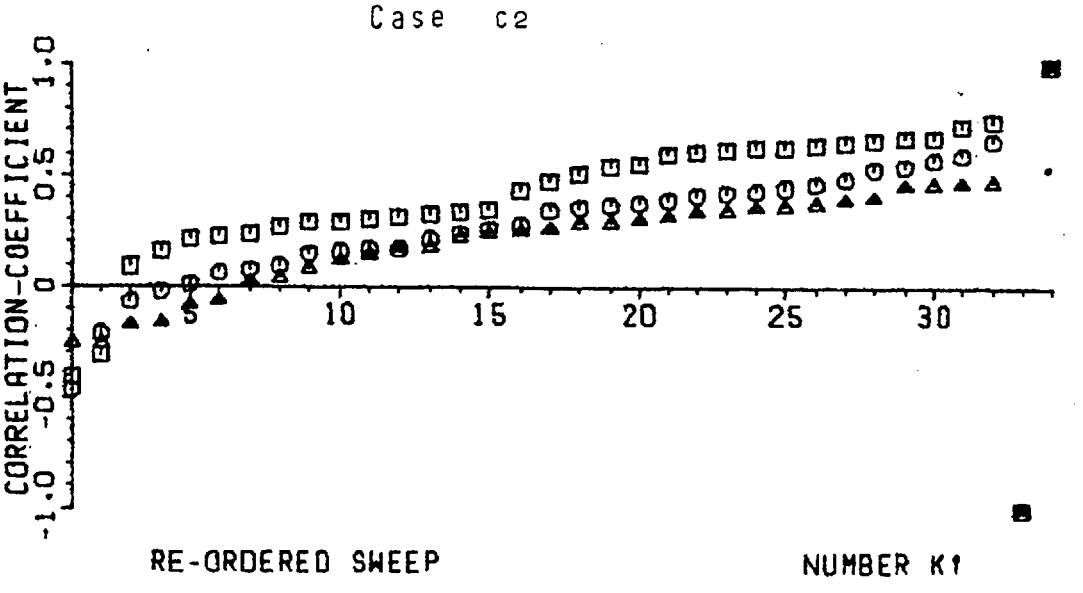


Fig. 3.9 Subject B - Case c.

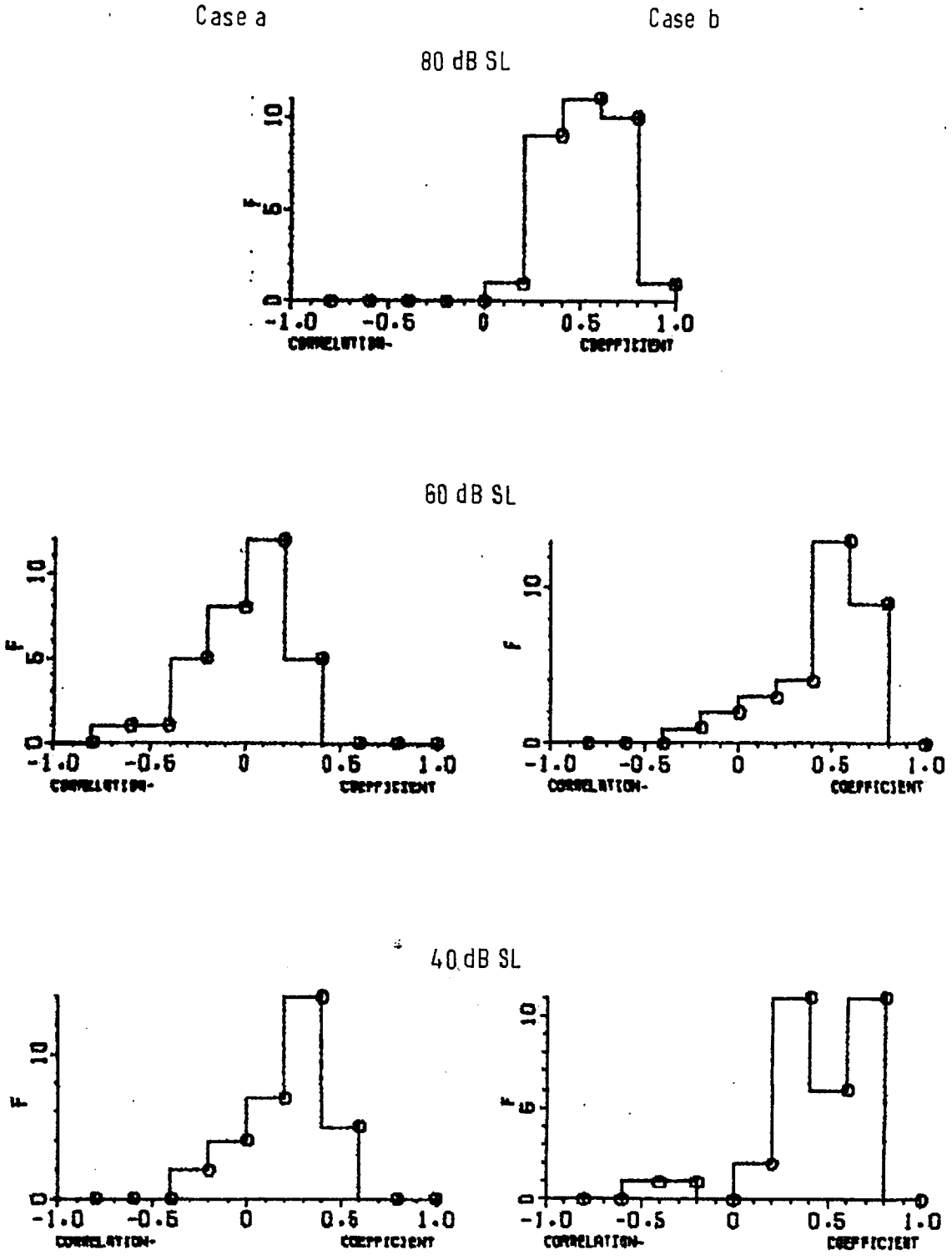
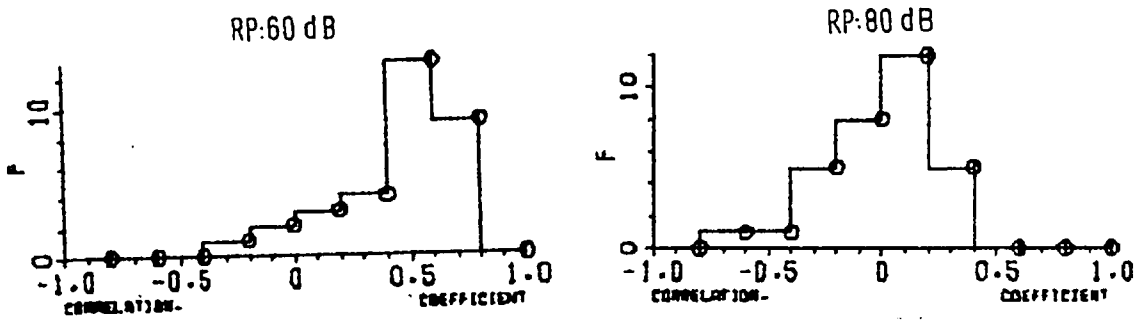


Fig. 3.10 Subject B - Cases a and b histograms.

Case c1



Case c2

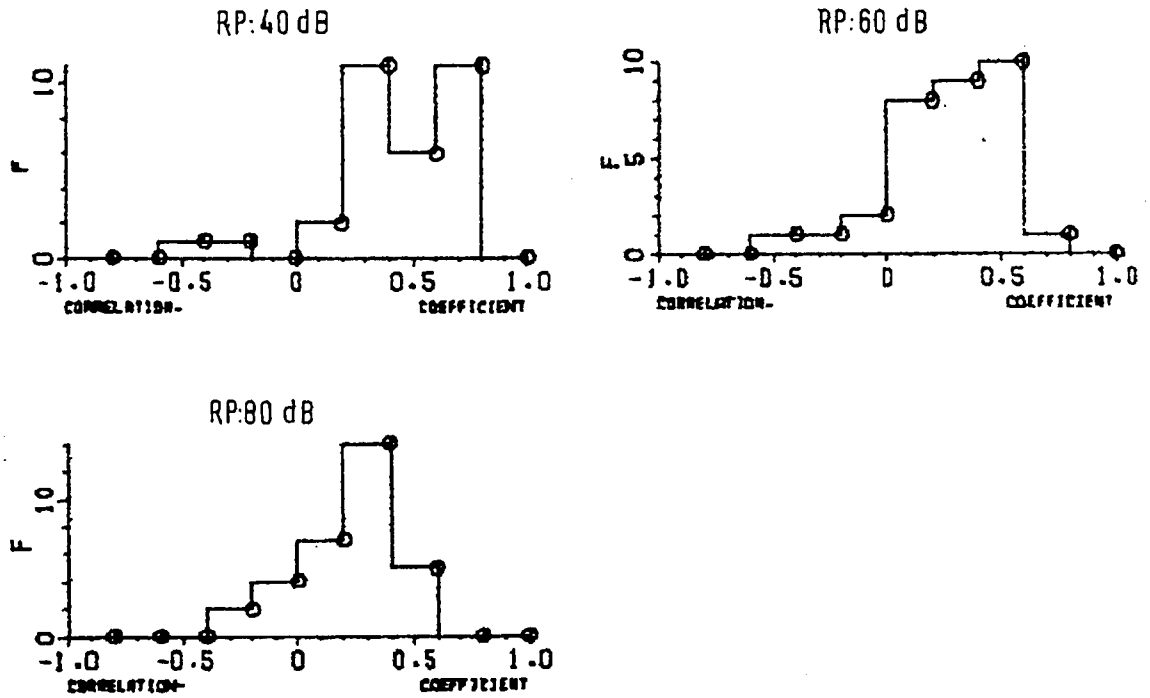
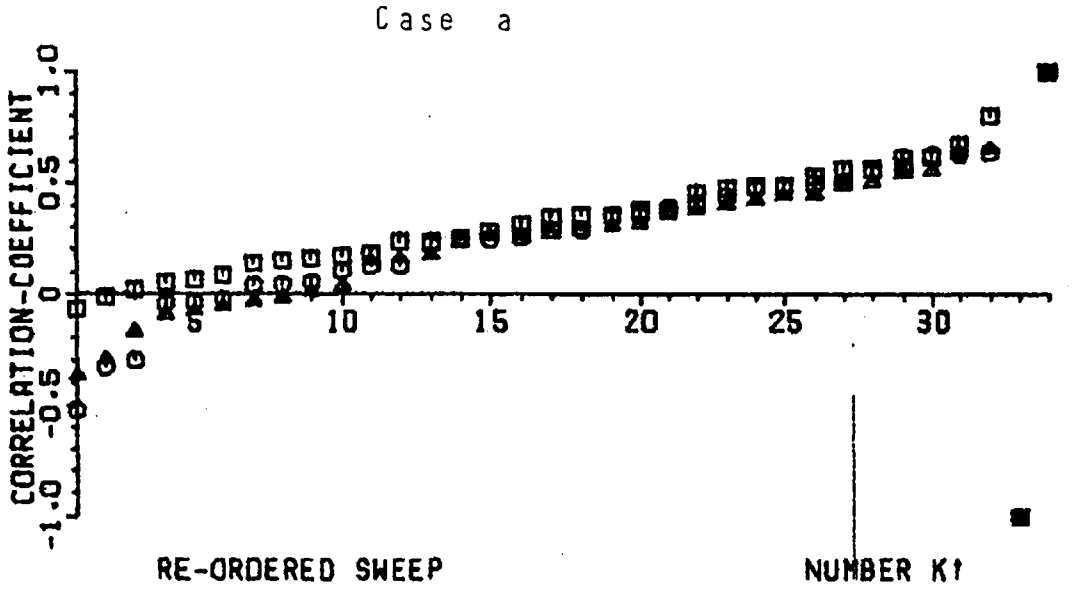


Fig. 3.11 Subject B - Case c histograms.



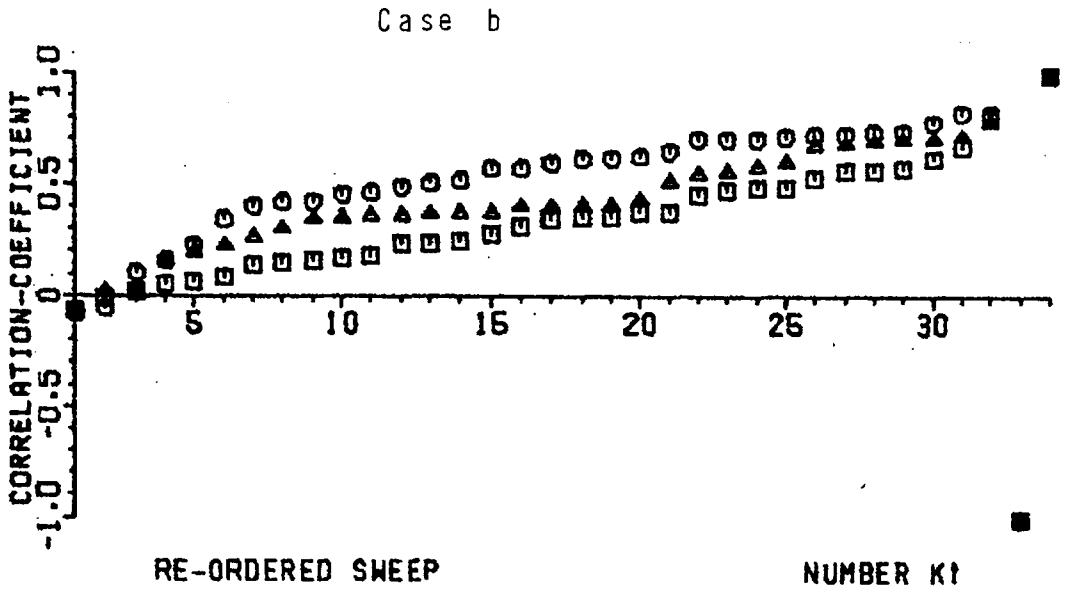
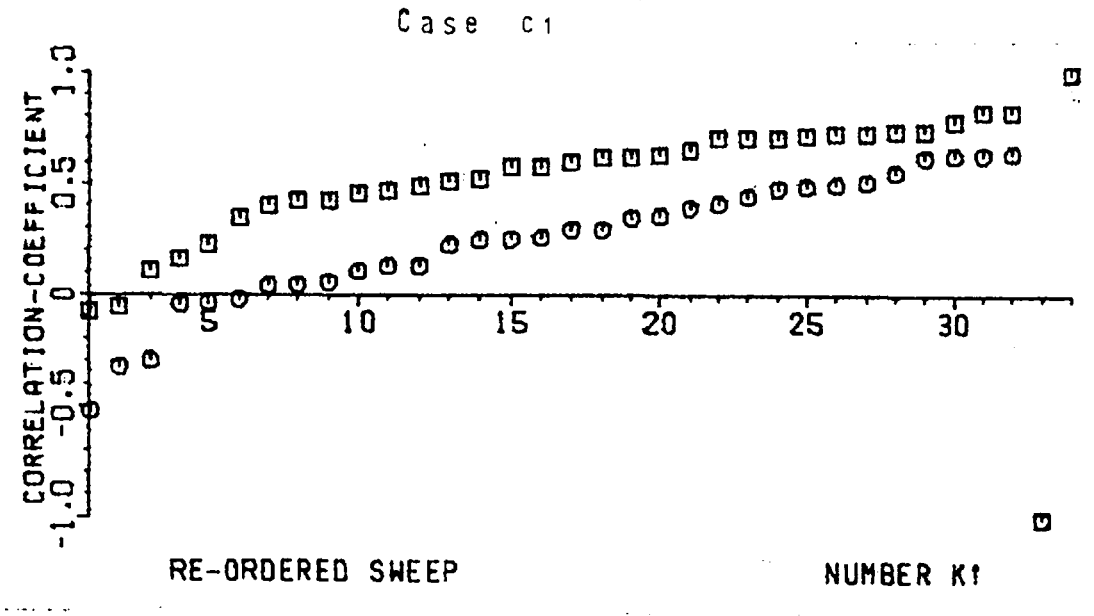


Fig. 3.12 Subject C - Cases a and b.



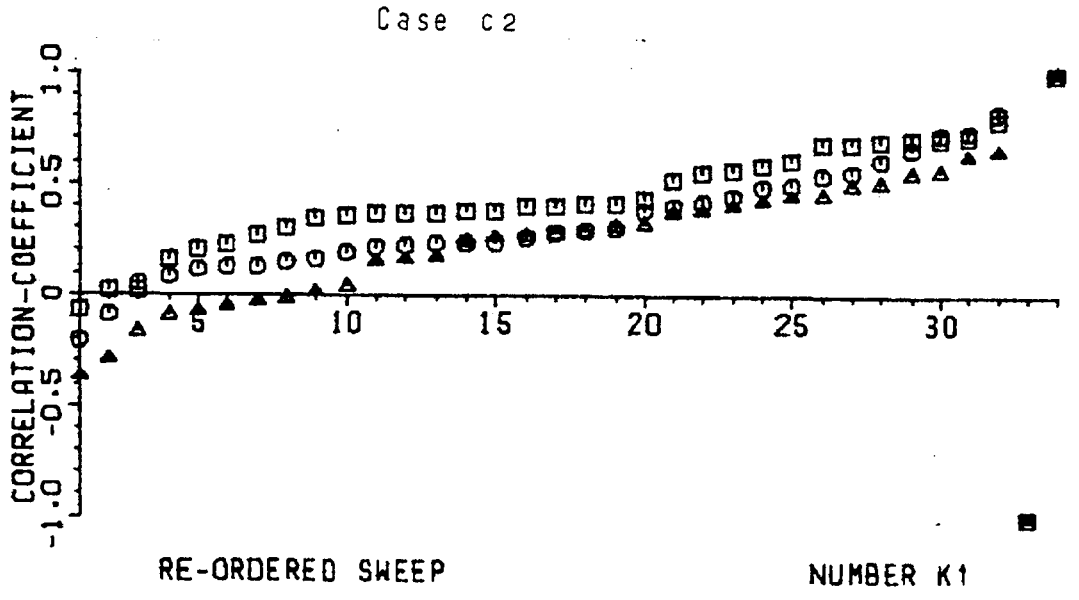


Fig. 3.13 Subject C - Case c.

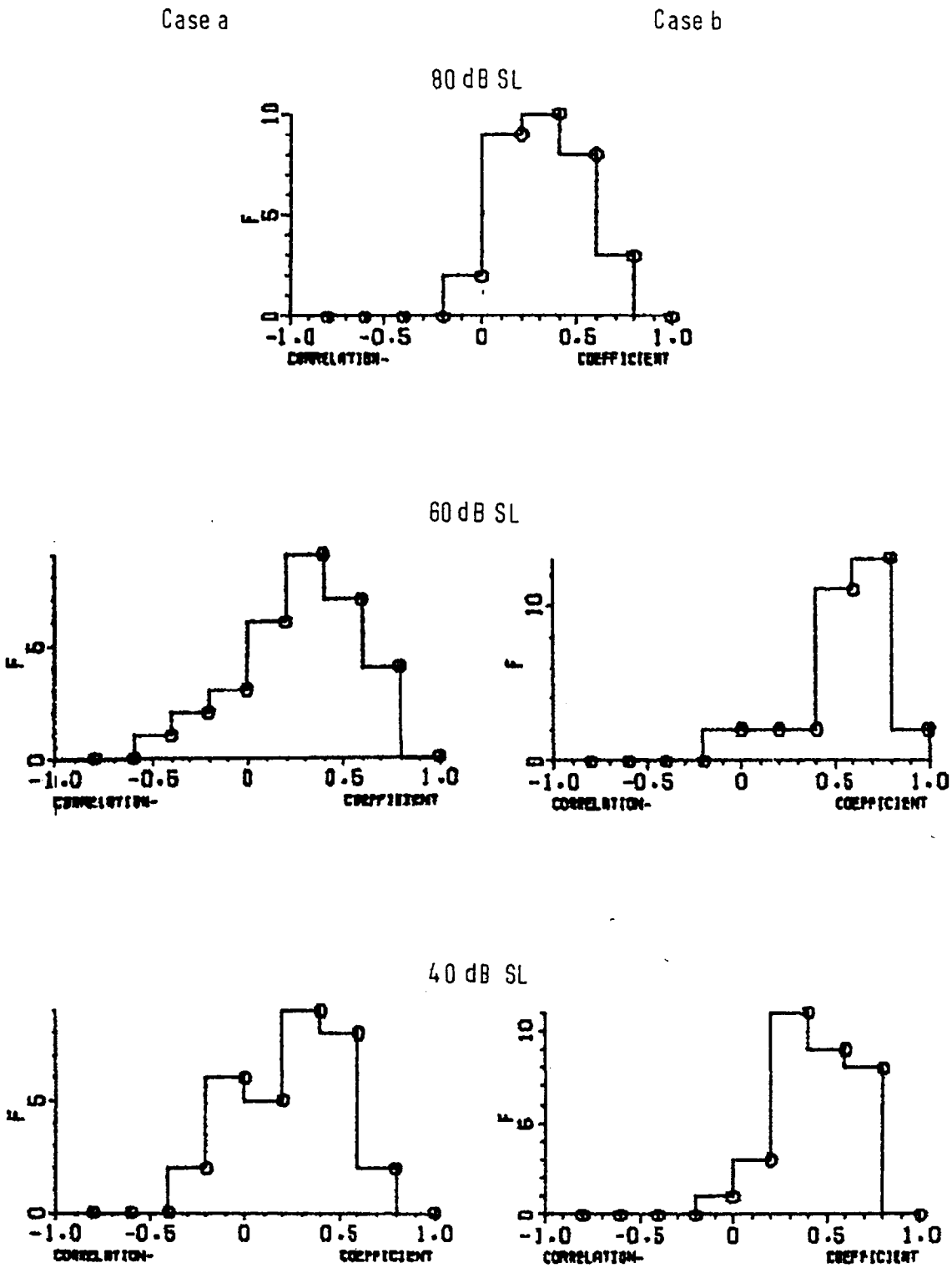


Fig. 3.14 Subject C - Cases a and b histograms.

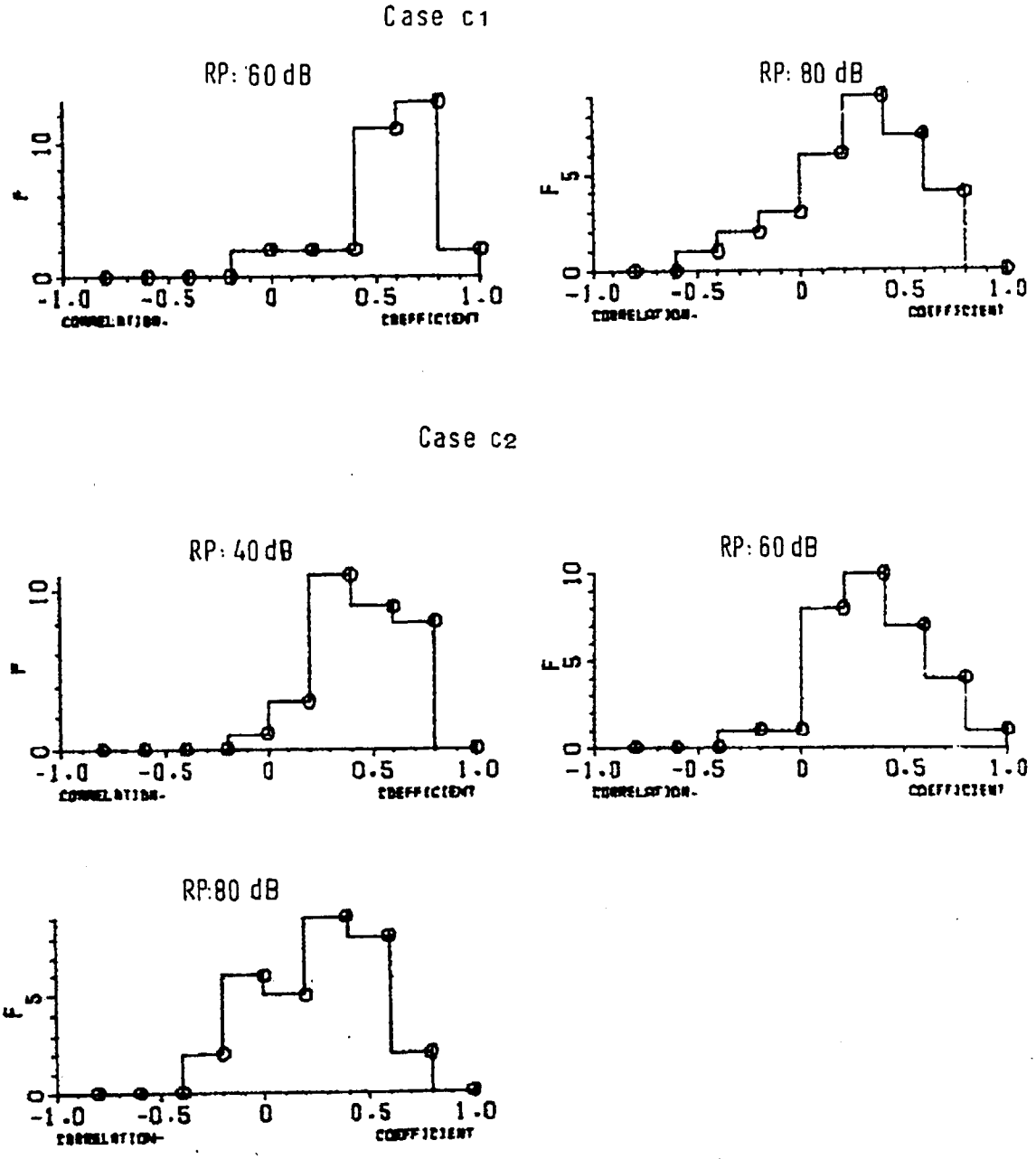


Fig. 3.15 Subject C - Case c histograms.

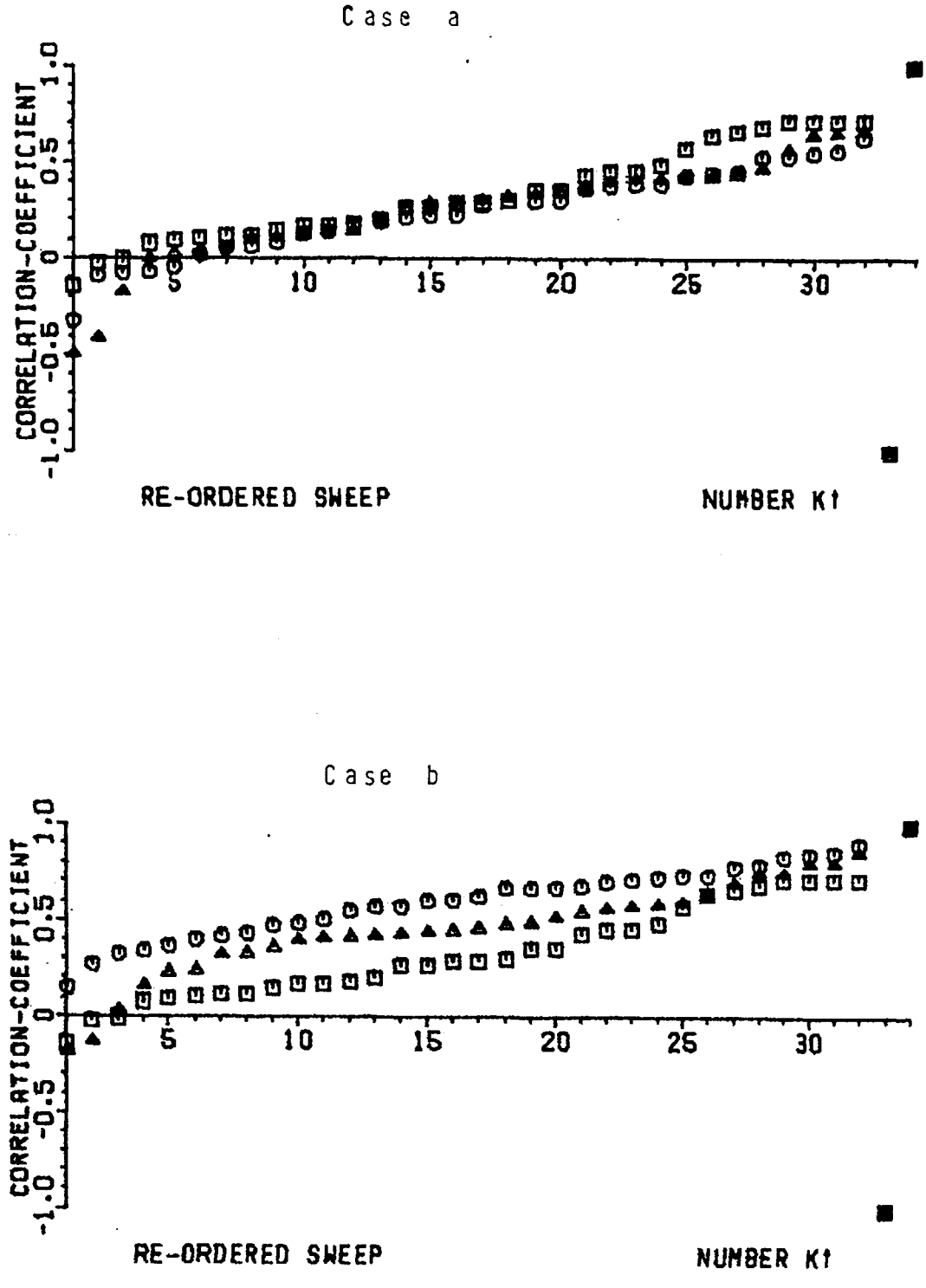
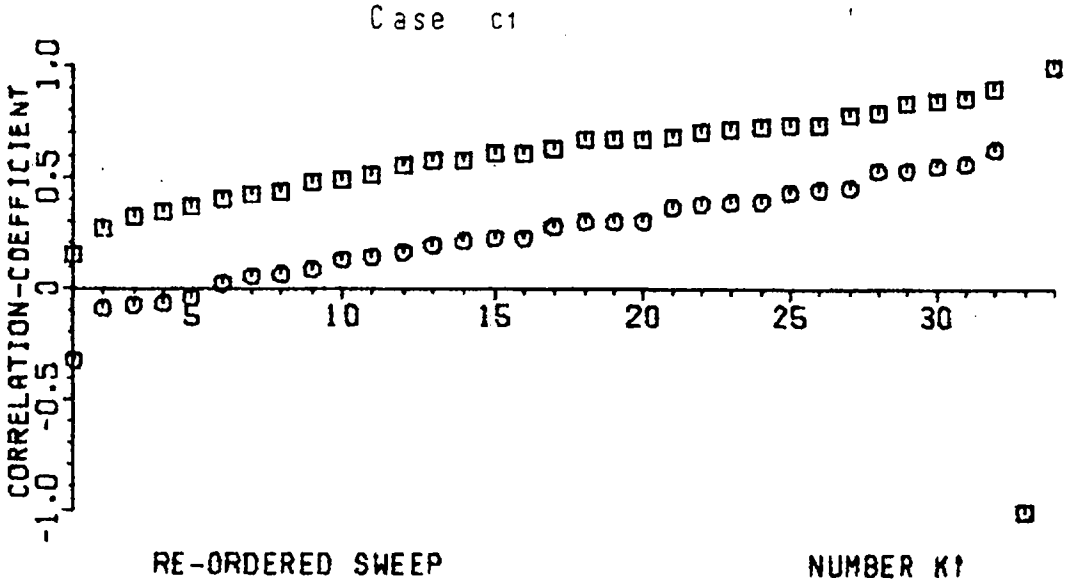


Fig. 3.16 Subject D - Cases a and b.



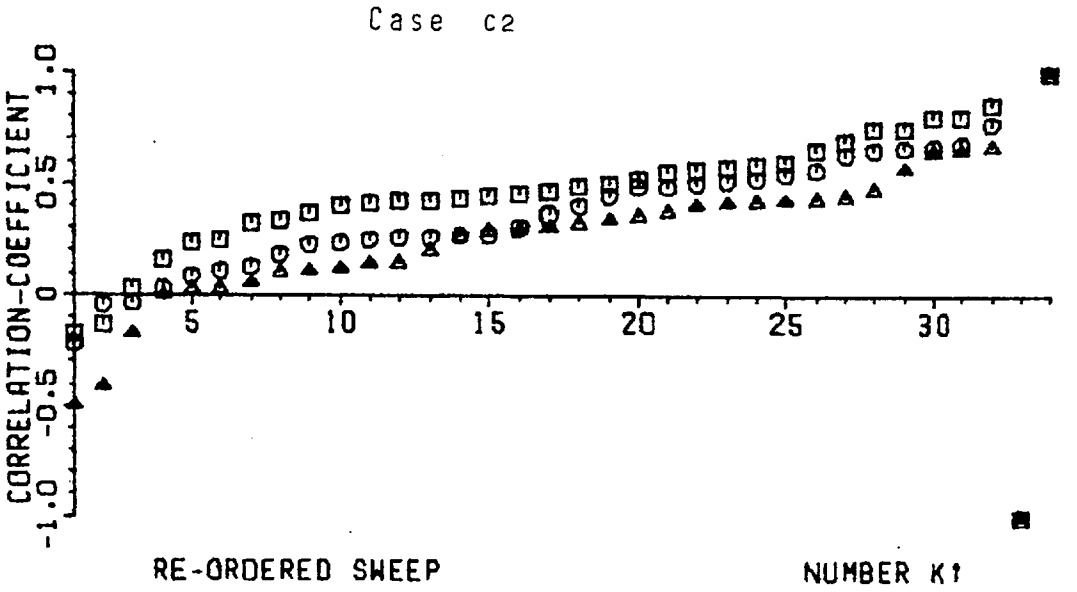


Fig. 3.17 Subject D - Case c.

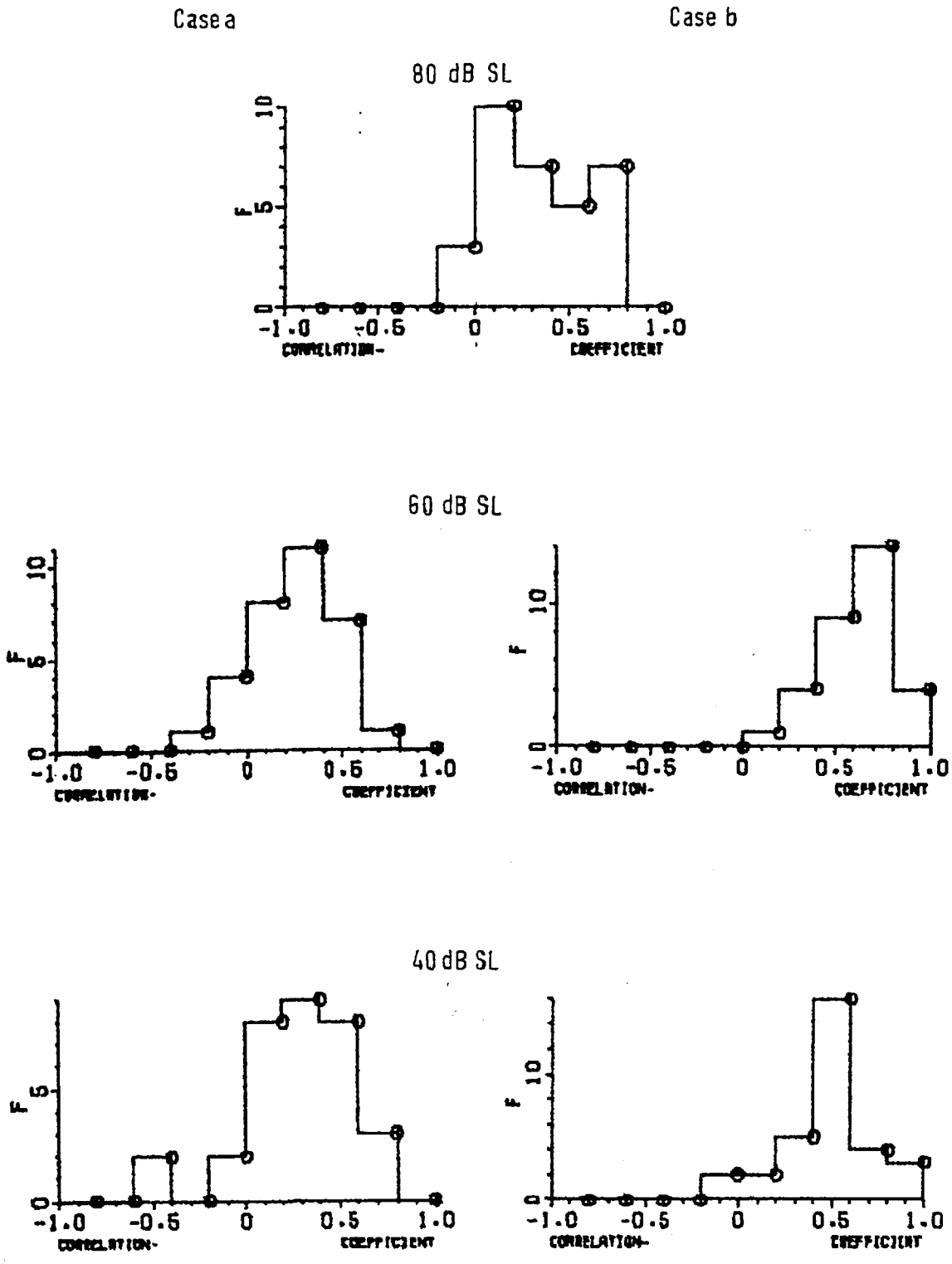
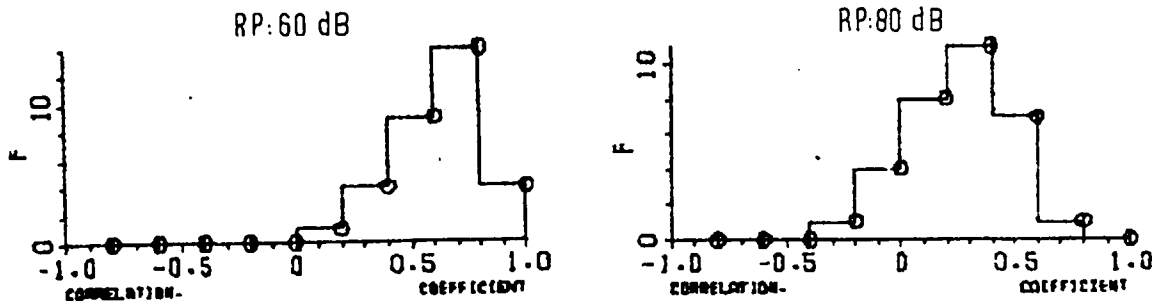


Fig. 3.18 Subject D - Cases a and b histograms.

Case c_1



Case c_2

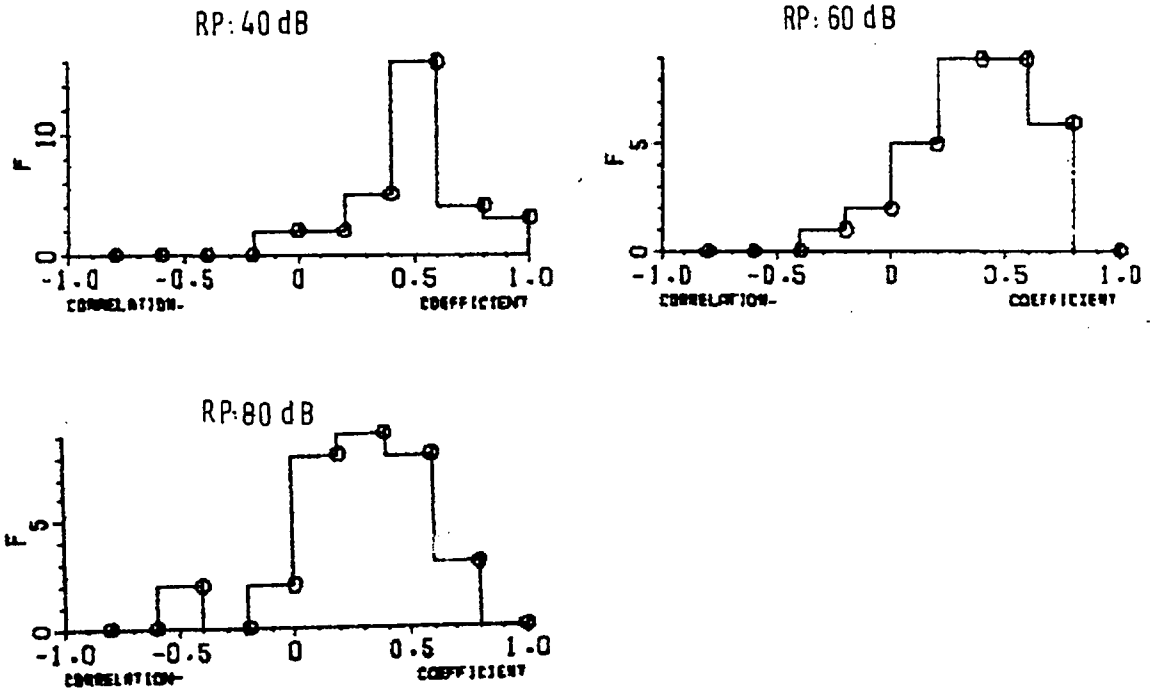
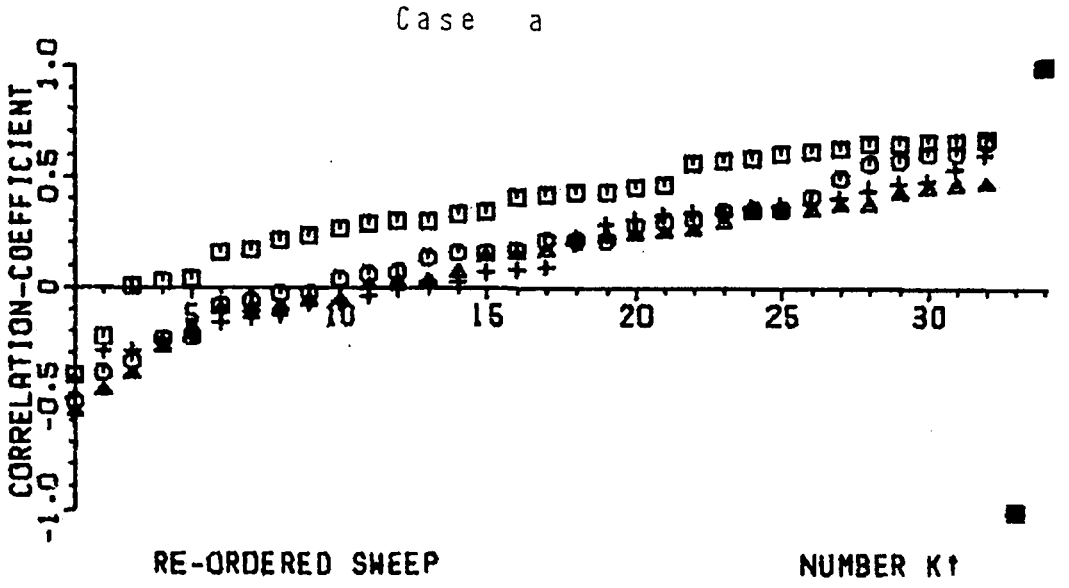


Fig. 3.19 Subject D - Case c histograms.



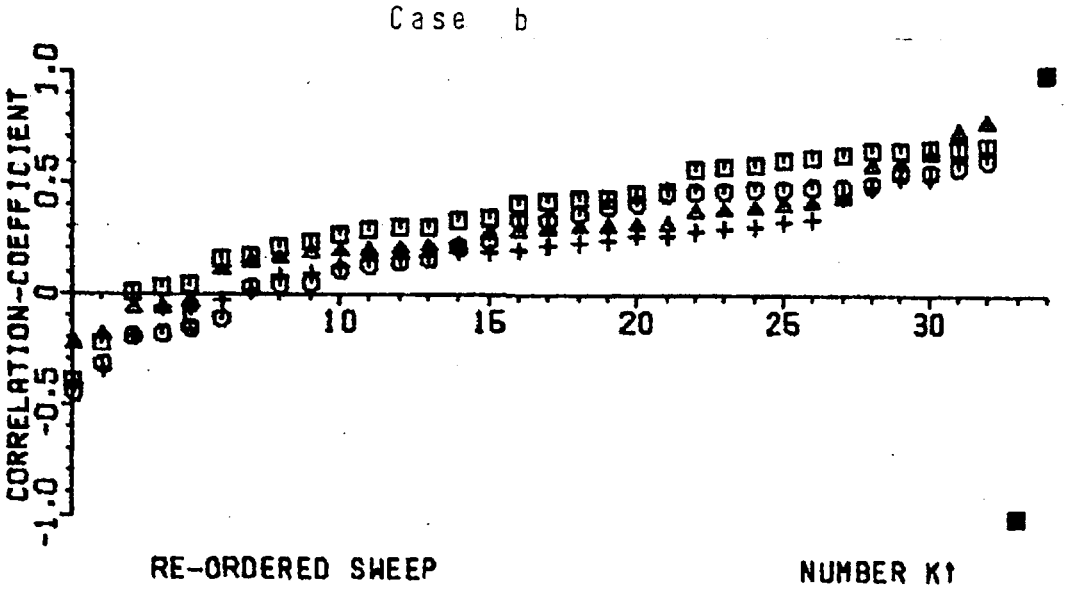


Fig. 3.20 Subject E - Cases a and b.

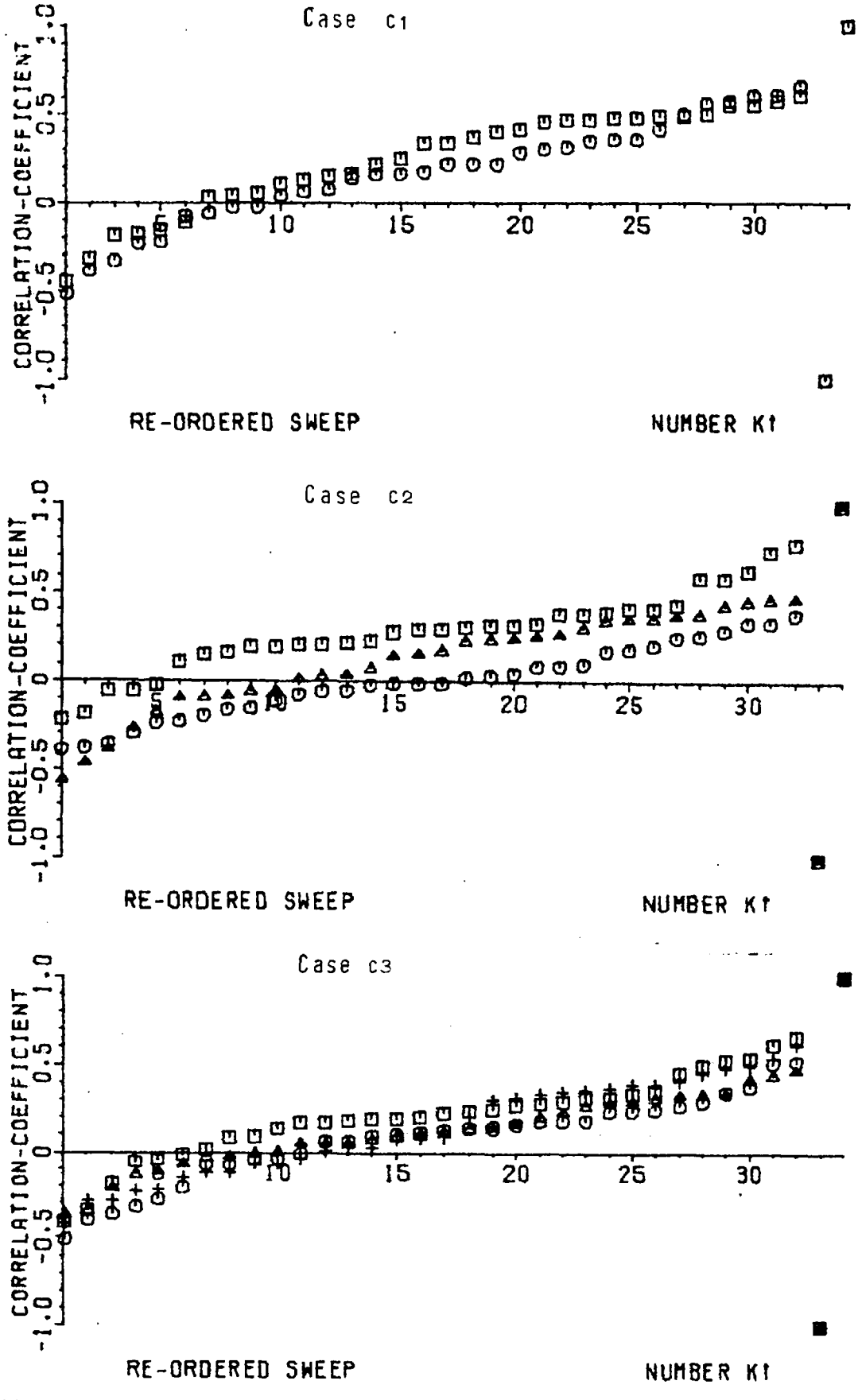


Fig. 3.21 Subject E - Case c.

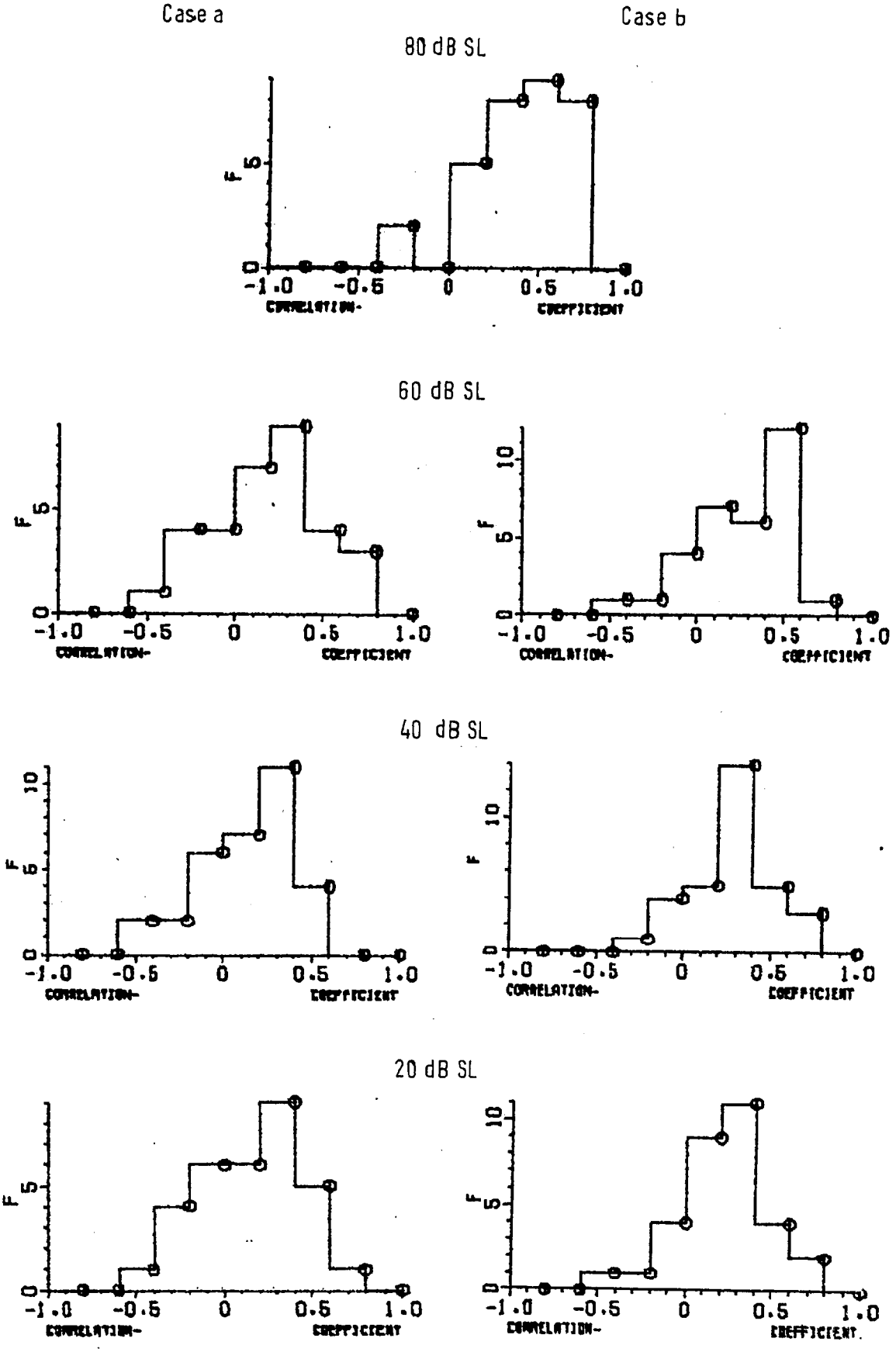


Fig. 3.22 Subject E - Cases a and b histograms.

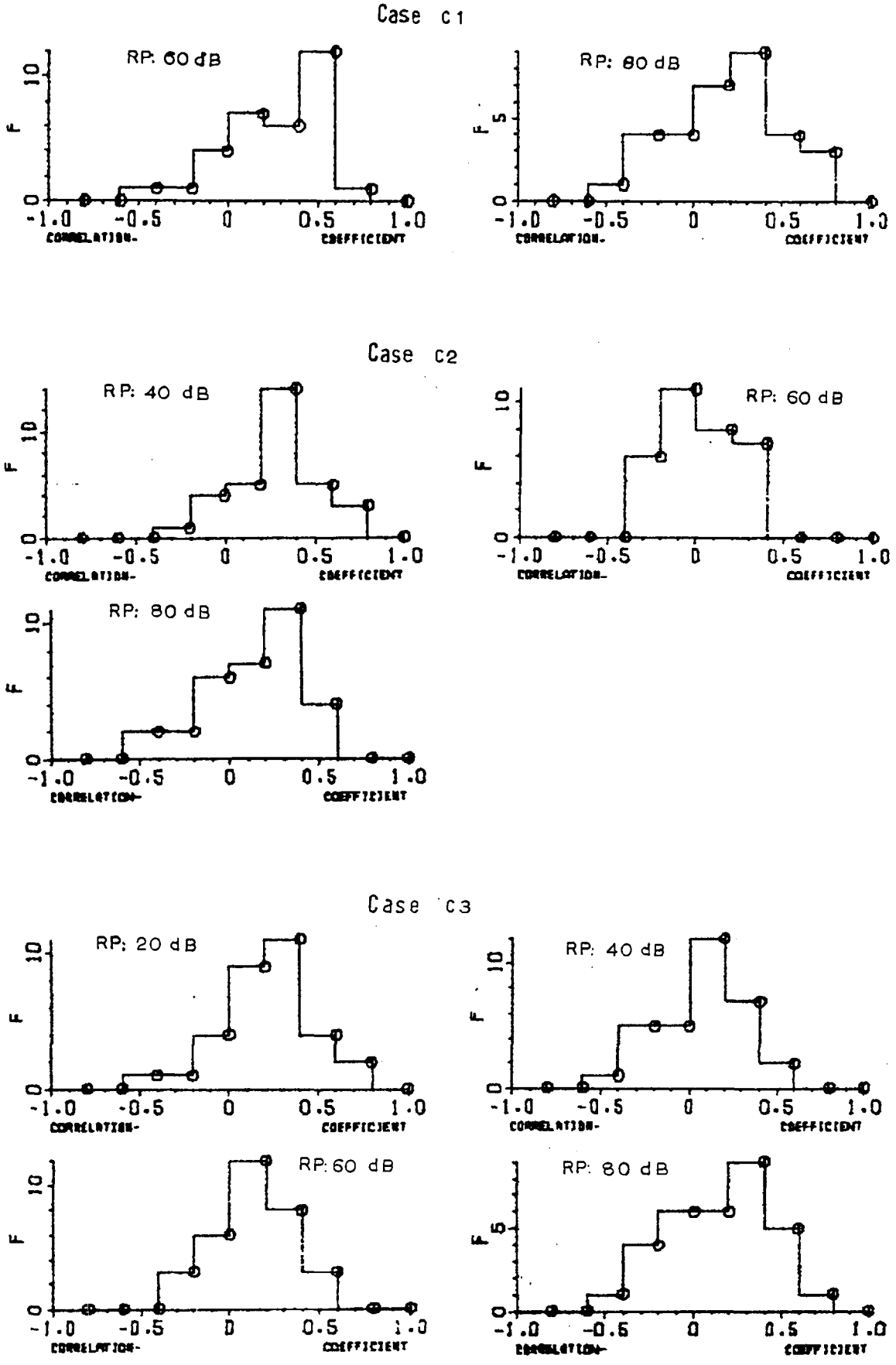


Fig. 3.23 Subject E - Case c histograms.

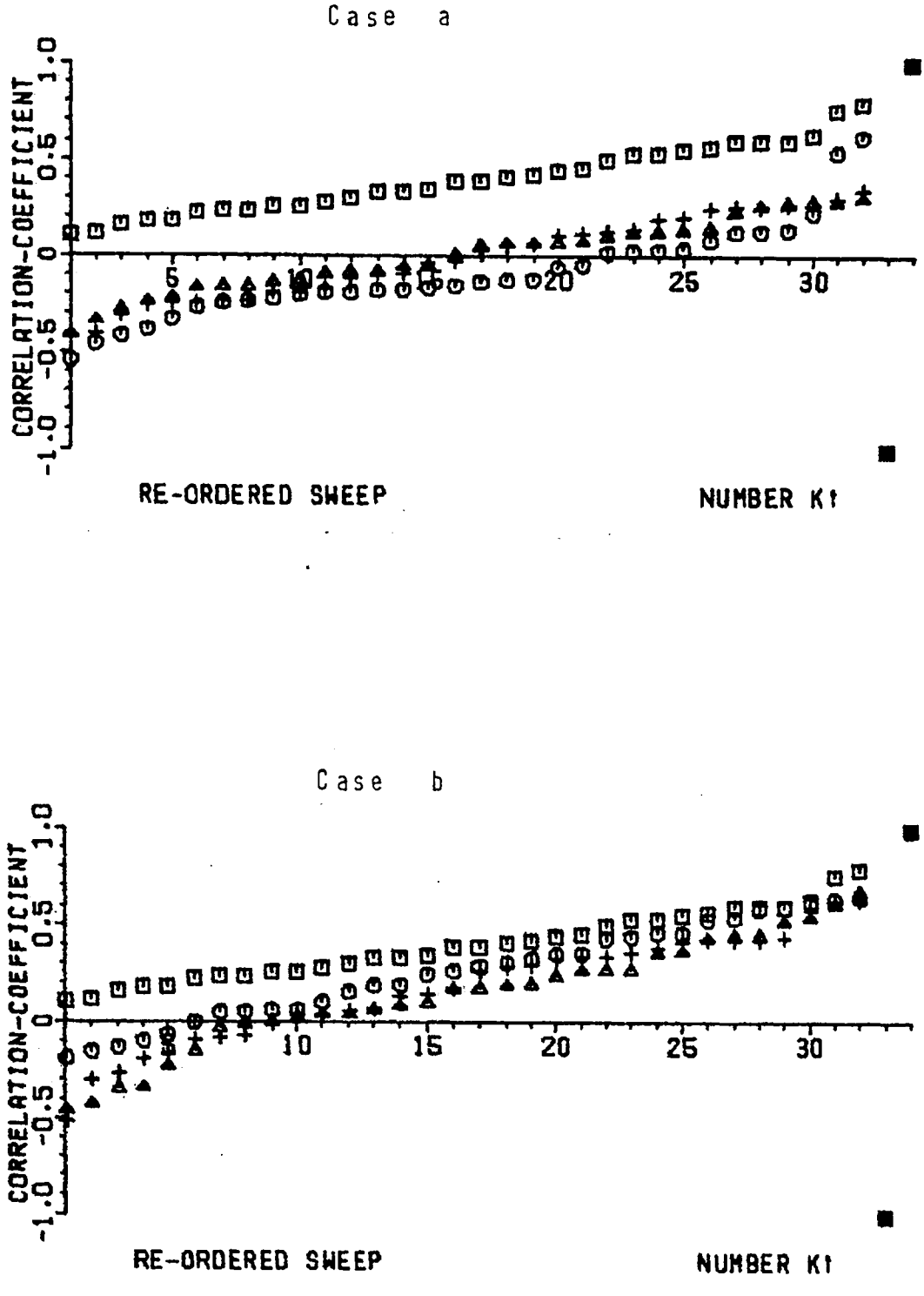


Fig. 3.24 Subject F - Cases a and b.

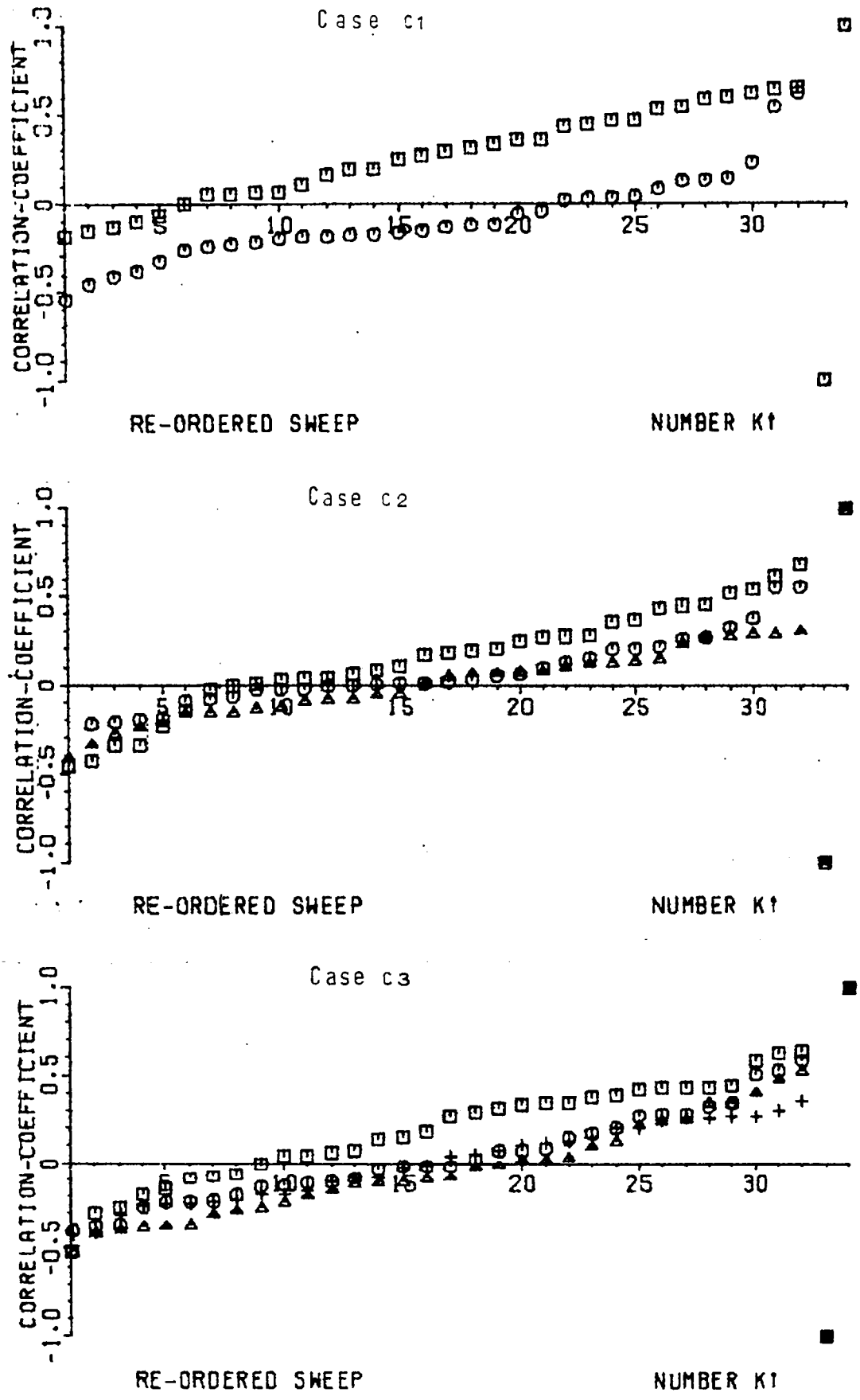


Fig. 3.25 Subject F - Case c.

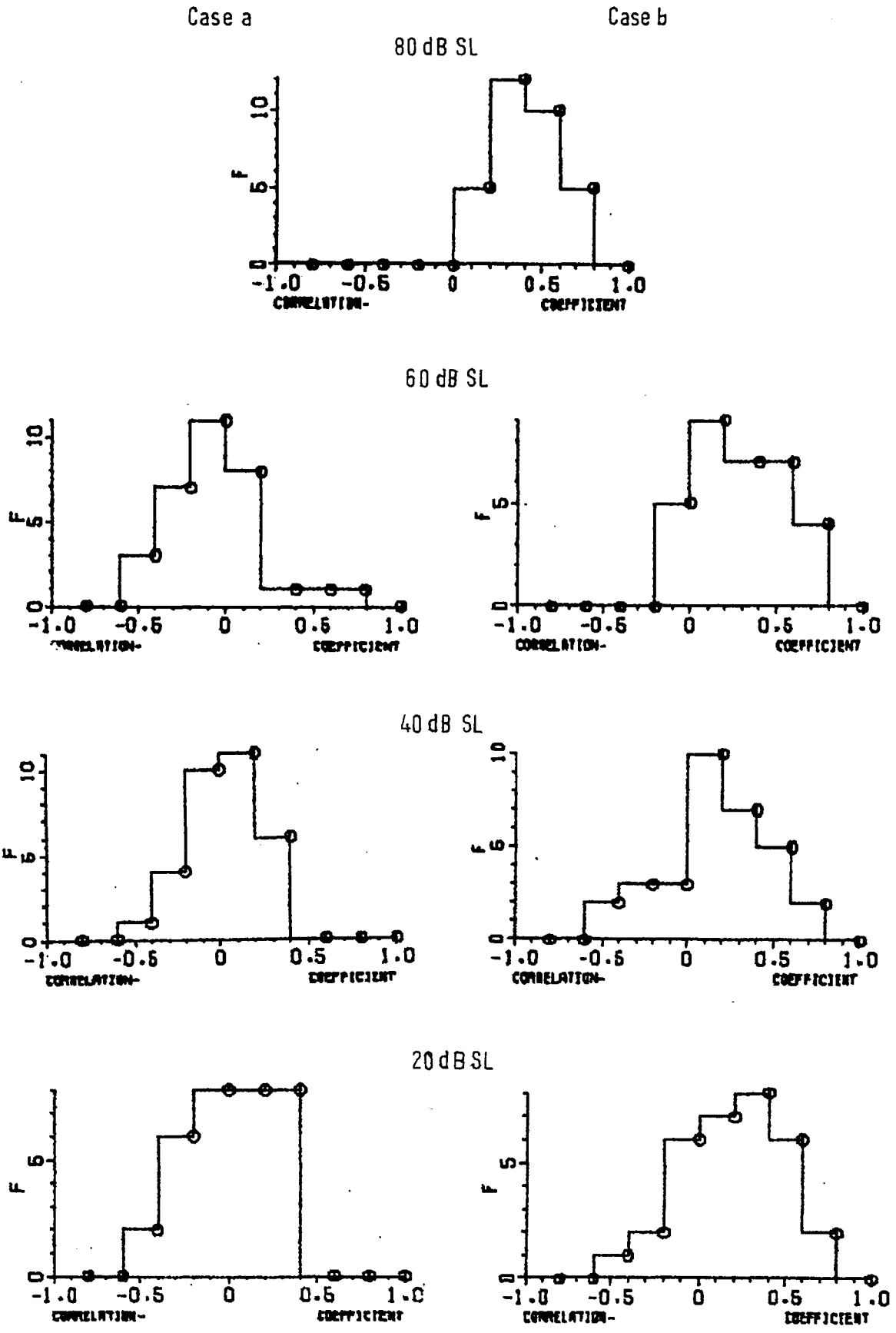


Fig. 3.26 Subject F - Cases a and b histograms.

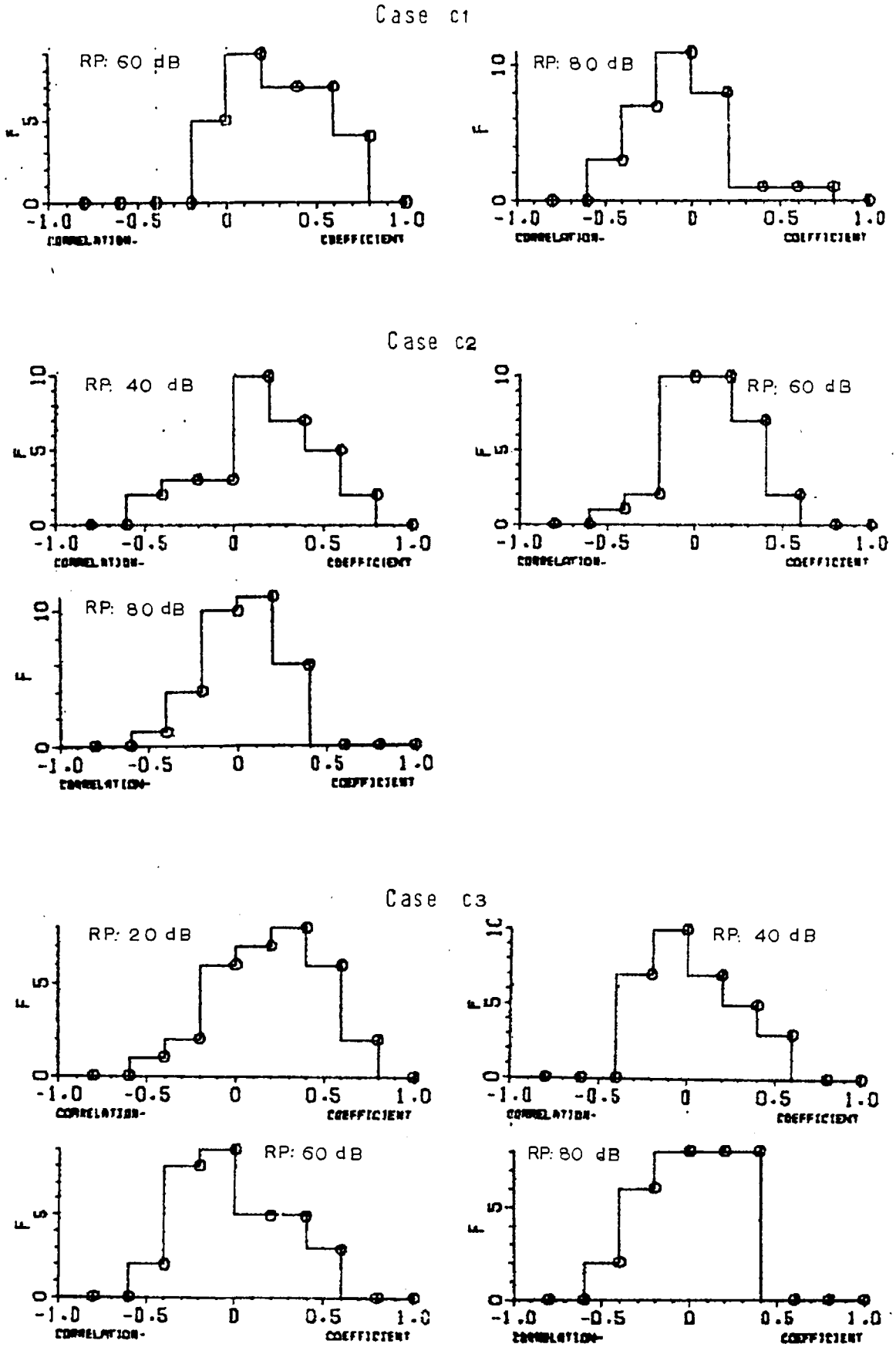


Fig. 3.27 Subject F - Case c histograms.

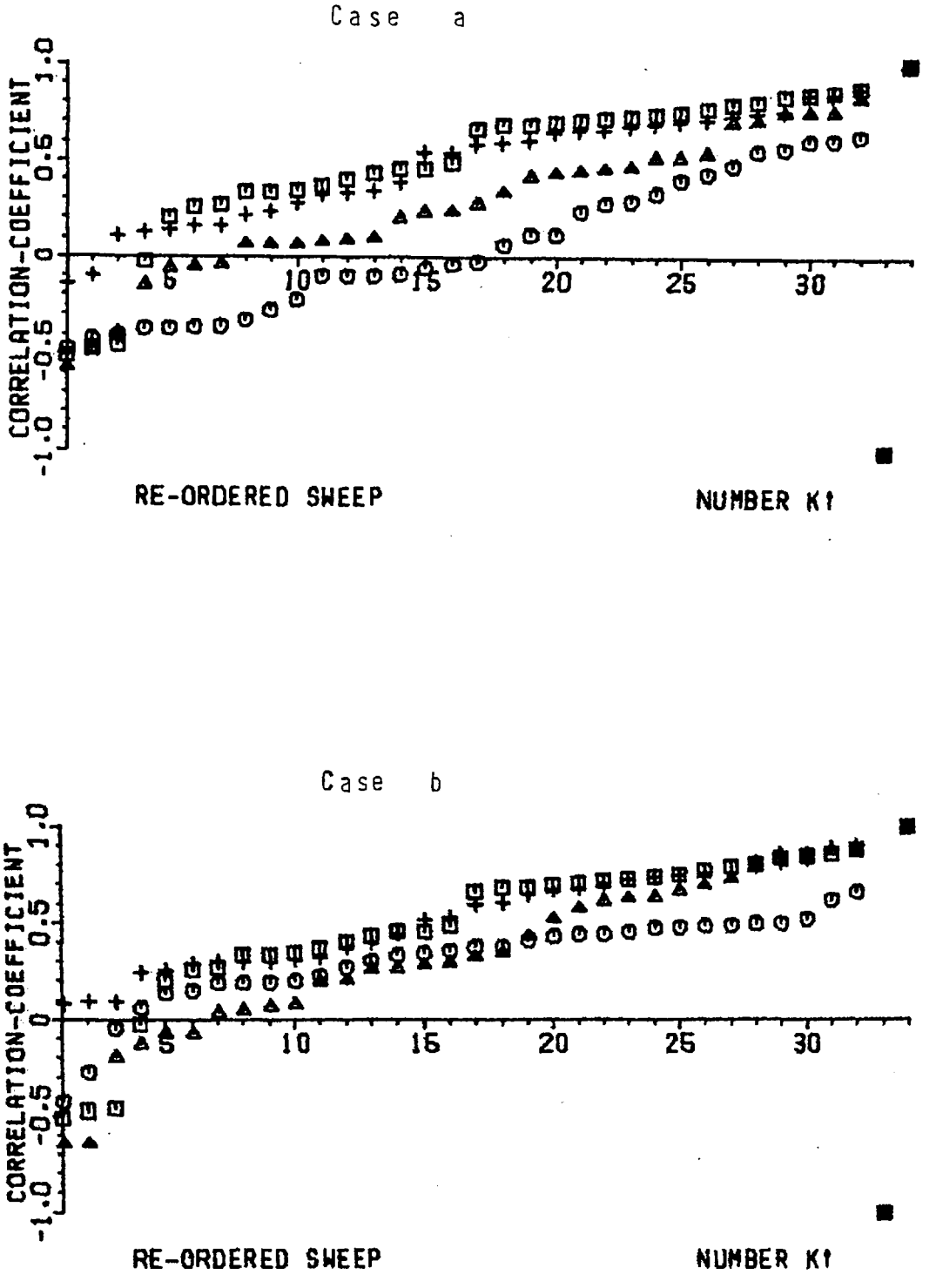


Fig. 3.28 Subject G - Cases a and b.

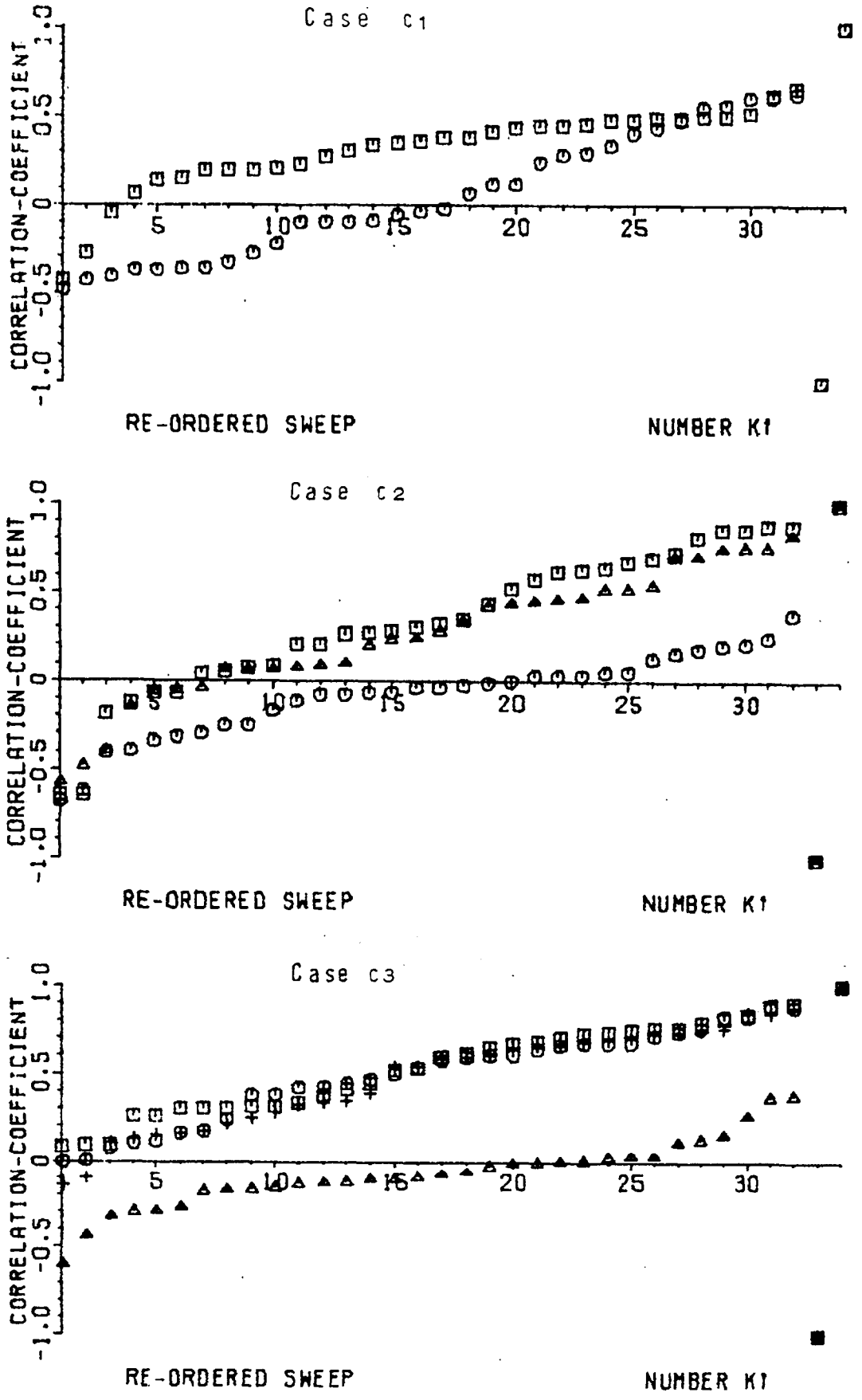


Fig. 3.29 Subject G - Case c.

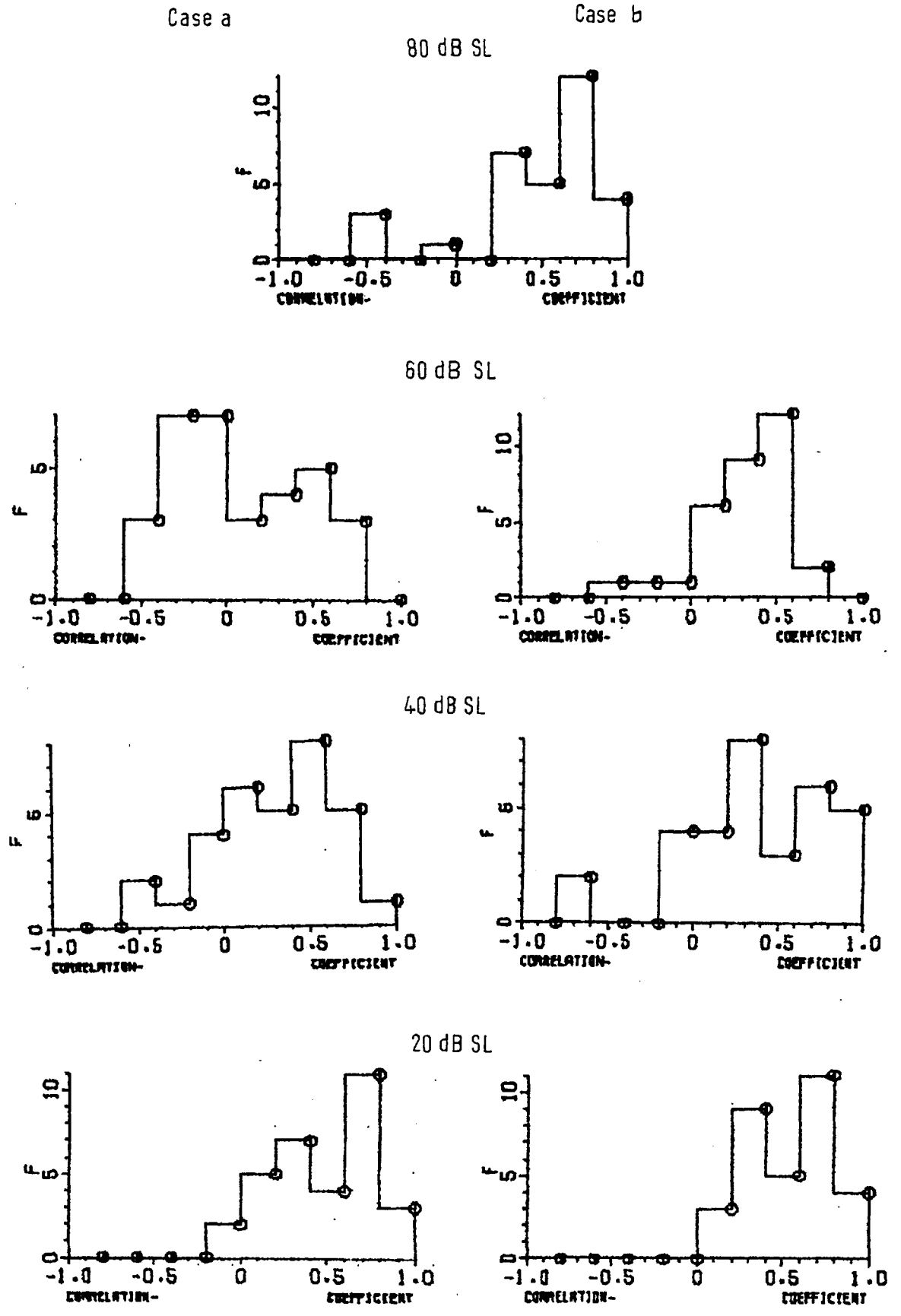


Fig. 3.30 Subject G - Cases a and b histograms.

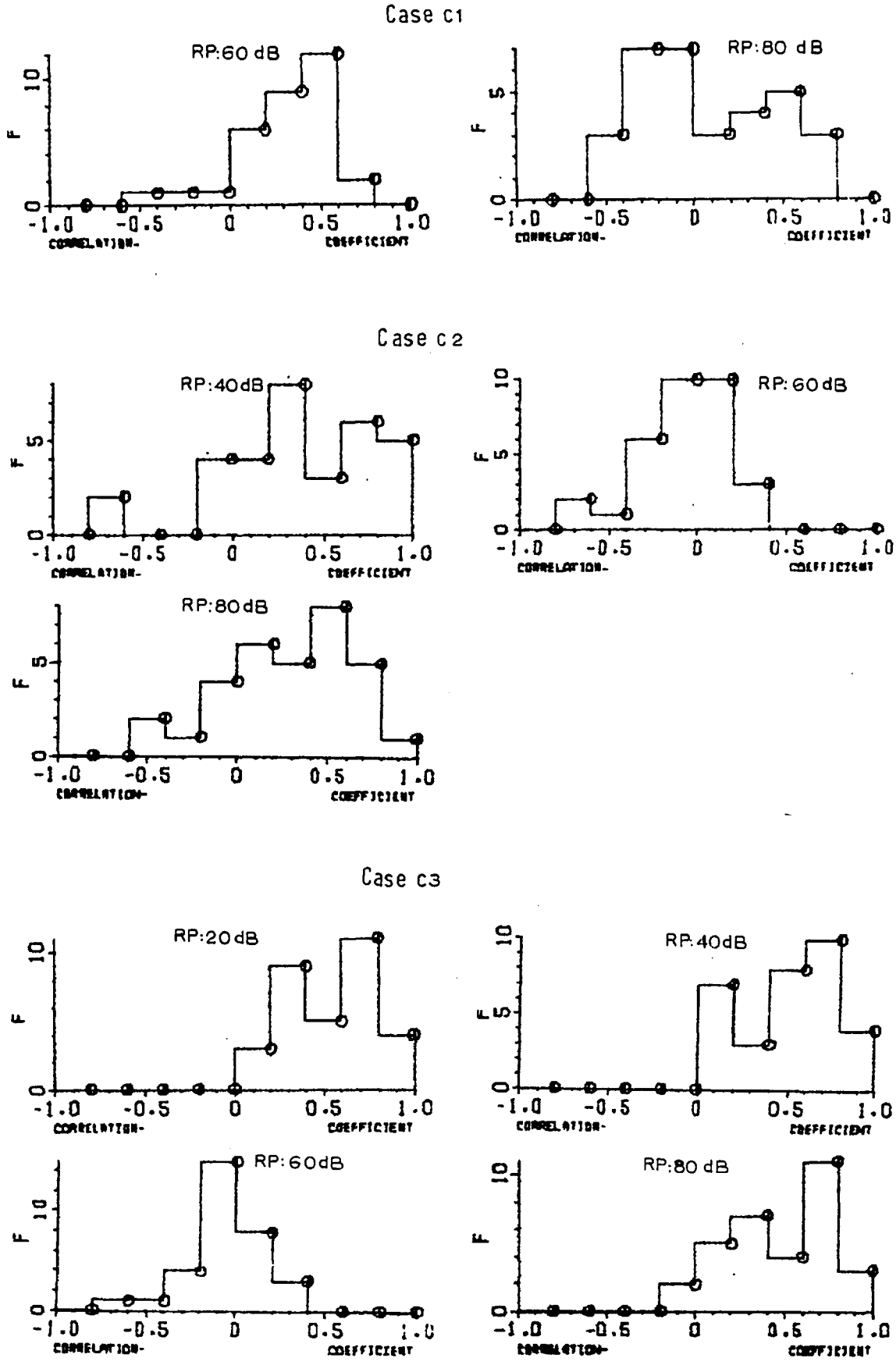
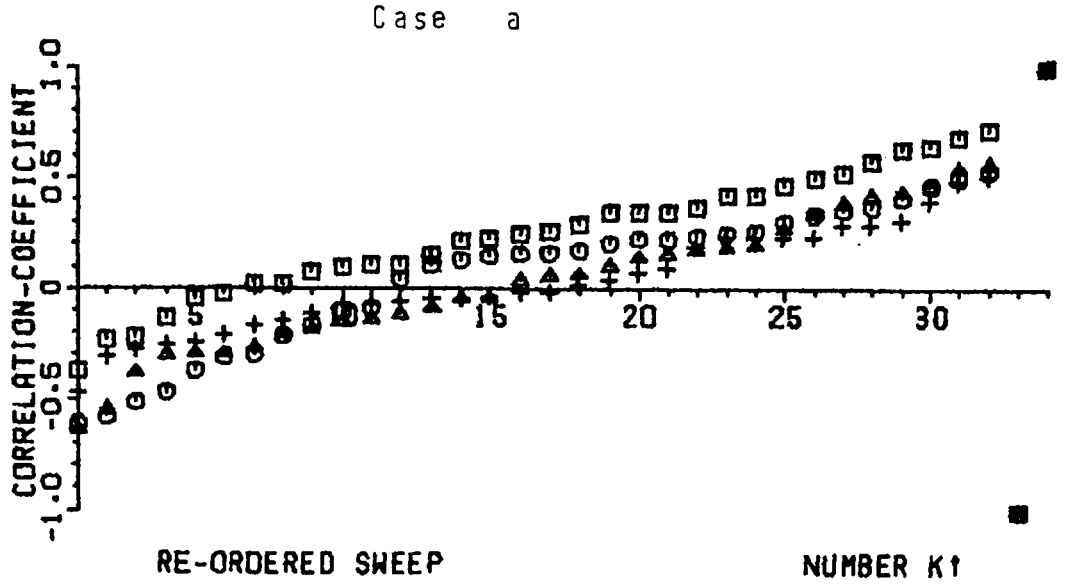


Fig. 3.31 Subject G - Case c histograms.



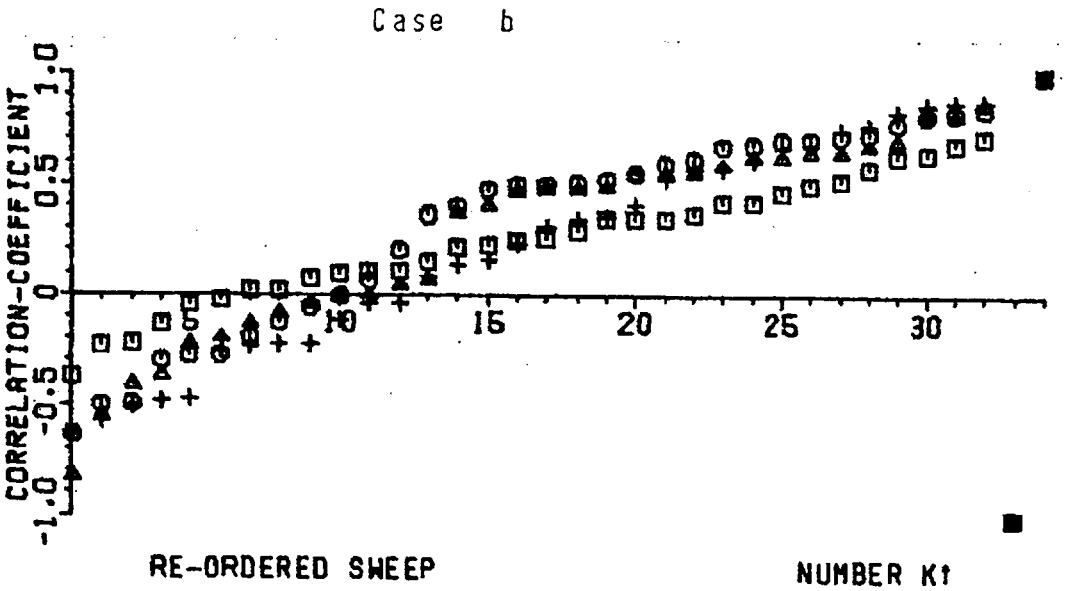


Fig. 3.32 Subject H - Cases a and b.

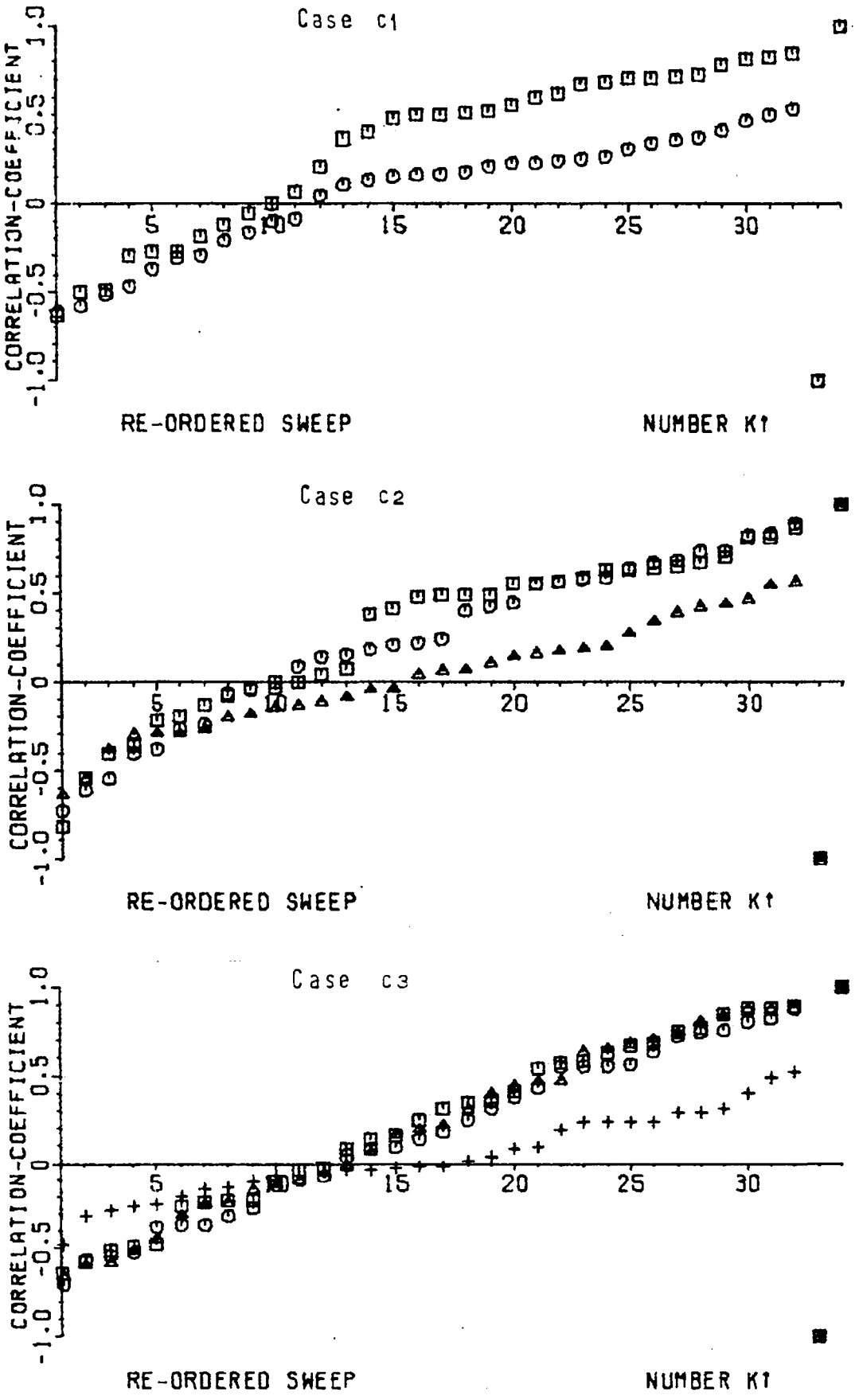


Fig. 3.33 Subject H - Case c.

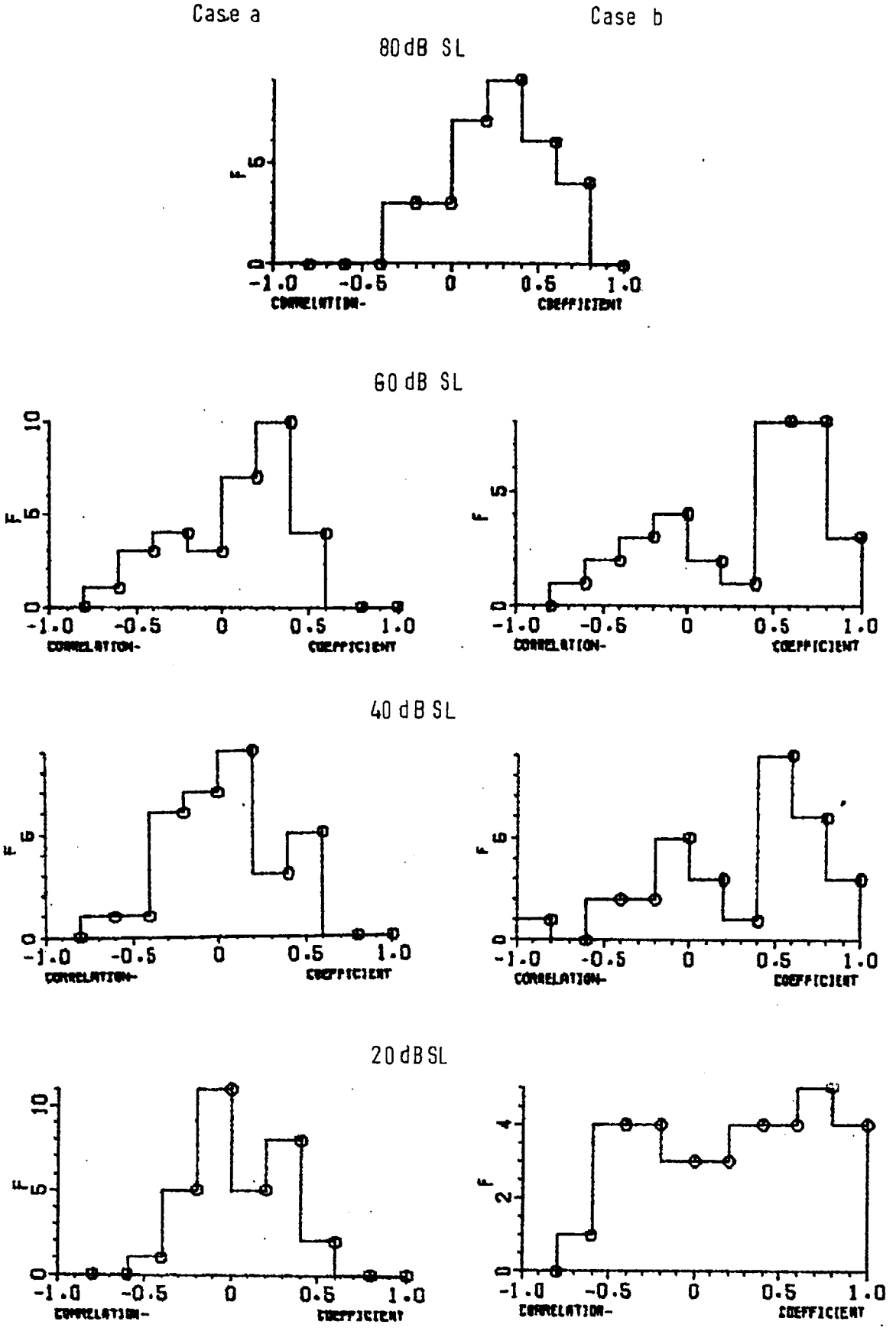


Fig. 3.34 Subject H - Cases a and b histograms.

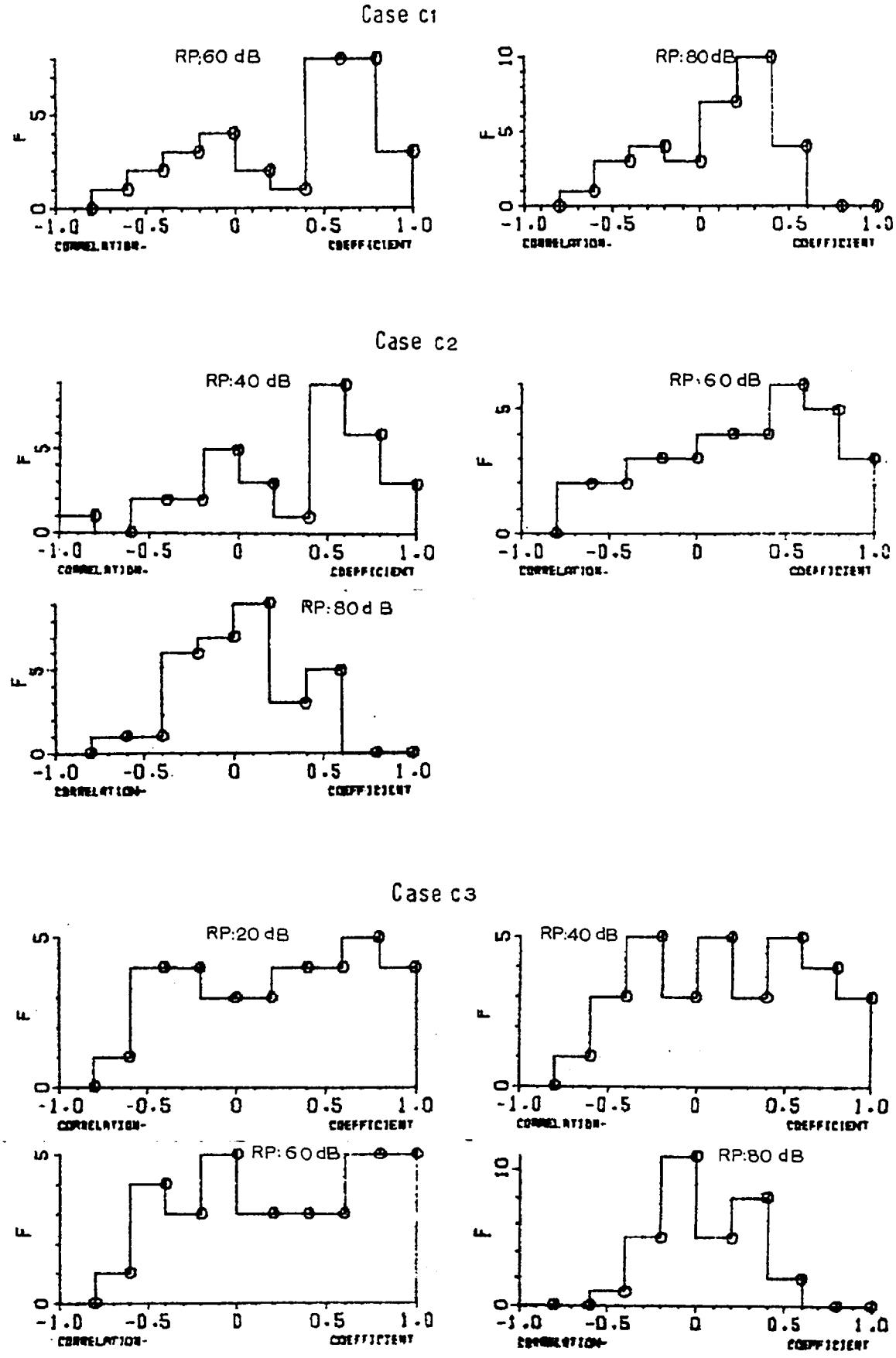


Fig. 3.35 Subject H - Case c histograms.

MEAN CORRELATION COEFFICIENT
(AND STANDARD ERROR) VALUES

Subaver.	SL (dB)	Reference Pattern SL (dB)			
		80	60	40	20
A	80	.555 (.04)			
	60	.517 (.04)	.553 (.04)		
	40	.339 (.04)	.337 (.04)	.513 (.04)	
B	80	.488 (.03)			
	60	.080 (.04)	.429 (.04)		
	40	.199 (.04)	.265 (.04)	.408 (.05)	
C	80	.321 (.04)			
	60	.242 (.05)	.526 (.04)		
	40	.227 (.05)	.321 (.04)	.423 (.04)	
D	80	.331 (.04)			
	60	.242 (.04)	.595 (.04)		
	40	.247 (.05)	.349 (.04)	.454 (.04)	
E	80	.362 (.05)			
	60	.170 (.05)	.241 (.05)		
	40	.108 (.05)	-.001(.04)	.278 (.04)	
	20	.132 (.05)	.110 (.04)	.070 (.04)	.202 (.04)
F	80	.397 (.03)			
	60	-.089(.04)	.262 (.04)		
	40	.015 (.04)	.061 (.04)	.146 (.05)	
	20	-.007(.04)	.044 (.05)	.027 (.05)	.177 (.05)
G	80	.469 (.07)			
	60	.050 (.06)	.309 (.04)		
	40	.259 (.06)	-.080(.04)	.328 (.07)	
	20	.469 (.05)	-.074(.04)	.490 (.05)	.524 (.04)
H	80	.242 (.05)			
	60	.059 (.06)	.309 (.08)		
	40	.027 (.05)	.232 (.08)	.271 (.08)	
	20	.036 (.04)	.199 (.09)	.161 (.08)	.216 (.08)

Table 3.1

CHAPTER 4

CONCLUSIONS

The design, construction and testing of the BSER Audiometer has been described. As the prototype model has been tested at the New Addenbrooke's Hospital (Cambridge) it has been found useful in the clinical environment and also that it facilitates research in the BSER field. At the time this thesis was written three more instruments were in test to be soon delivered. Unfortunately more time than expected was spent on the construction of those three more instruments, though it was profitable because it allowed to improve some of the features of the prototype model. Some suggestions for further improvement can be made which could be incorporated in a later version of the instrument. They can be summarized as follows:

-Speed motor control. The speed of the chart recorder motor is voltage controlled, which gives an accuracy of ±2%. Improvement on this accuracy could be achieved by a speed control; this would lead to a more straightforward determination of the peak latencies, which could be read off a standard scale.

-Include a voltage calibration signal.

-Provide a monitor O/P for both the EEG signal response and the click mark for use in recording individual responses for further analysis.

APPENDIX A

BSER AUDIOMETER SOFTWARE

```
                                IDENT    BSER
0000                            PROGRAM
                                LIST     G
0000                            ORG      0#0000
0000  00

                    *           THIS IS THE SOFTWARE TO CONTROL
                    *           THE BSER AUDIOMETER.
                    *           IT STARTS AT #0000.

                    *           INITIALISATION

0000                            LDI      0#07    :INITIALIZE R4 TO BE
0000  F8
0001  07
0002                            PLO      R4      :USED AS A PROGRAM
0002  A4
0003                            LDI      0#00    :COUNTER. (PC)
0003  F8
0004  00
0005                            PHI      R4
0005  B4
0006                            SEP      R4      :CHANGE PC TO R4.
0006  D4
0007                            PHI      R5      :SET R5.1 TO #00.
0007  B5
0008                            PLO      R2      :SET R2.0 TO #00.
0008  A2

                    *           THE 160*3 LOCATIONS TO STORE DATA
                    *           ARE ASSIGNED FROM #03EF TO #0210

0009                            LDI      0#FE
0009  F8
000A  FE
000B                            PLO      R9      :SET R9 TO #03EF
000B  A9
000C                            LDI      0#03
000C  F8
000D  03
000E                            PHI      R9
000E  B9
000F                            PLO      R5      :SET R5.0 TO #03.
000F  A5
0010                            PLO      R11     :SET R8.0 TO #03.
0010  AB
0011                            SEX      R9
0011  E9

                    *           THE 160*3 LOCATIONS BETWEEN #03EF
                    *           AND #0210 ARE CLEARED.

0012                CLE1        LDI      0#A9
0012  F8
0013  A9
0014                            PLO      R10     :SET RA.0 TO #A9.
0014  AA
0015                CLE2        GHI      R5
0015  95
0016                            STXD             :STORE #00 IN M(R9).
0016  73
0017                            DEC      R10
0017  2A
0018                            GLO      R10
```

```
0018 3A
0019
0019 3A
001A 15
001B
001B 23
001C
001C 83
001D
001D 3A
001E 12
001F
001F F8
0020 01
0021
0021 BC
0022
0022 59
0023
0023 19
0024
0024 19
0025
0025 99
0026
0026 B7
0027
0027 89
0028
0028 A7
0029
0029 19
002A
002A F8
002B 7F
002C
002C 59
002D
002D 19
002E
002E 19
002F
002F F8
0030 21
0031
0031 59
0032
0032 19
0033
0033 64
0034
0034 F8
0035 06
0036
0036 59
0037
0037 19
0038
0038 7B
0039
0039 6A
003A
003A 7A
003B
003B 57
003C
003C F8
0030 0C
003E
003E F2
003F
003F AC
0040
0040 19
0041
0041 F8
0042 FF
0043
0043 59
0044
```

```
        BNZ     CLE2
        DEC     R11
        GLO     R11
        BNZ     CLE1
        LDI     0#01
        PHI     R12     :SET RC.1 TO #01.
        STR     R9      :STORE #01 IN #0203.
        INC     R9
        INC     R9
        GHI     R9
        PHI     R7      :SET R7 TO #0205.
        GLO     R9
        PLO     R7
        INC     R9
        LDI     0#7F
        STR     R9      :STORE #7F IN #0206.
        INC     R9
        INC     R9
        LDI     0#21
        STR     R9      :STORE #21 IN #0208.
        INC     R9
        OUT     4       :SWITCH OFF TAPE RECORDER
        LDI     0#06    :CIRCUITS AND LEDS.
        STR     R9      :STORE #06 IN #020A.
        INC     R9
        SEQ             :Q=1, F1,F2,F3,F4 ARE AT
        INP     2       :I P PORT. READ THEM.
        REQ             :RESET Q.
        STR     R7
        LDI     0#0C
        AND             :STORE F4,F3 IN #020B.
        PLO     R12     :SET RC.0 TO #F4F3.
        INC     R9
        LDI     0#FF
        STR     R9      :STORE #FF IN #020C.
        SEX     R7
```

```
0044 F7                 GLO     R5
0045                    AND
0045 F2                 STR     R7      :STORE F2,F1 IN #0205.
0046                    GLO     R5
0046 57                 SM              :TEST VALUE IN #0205.
0047                    INC     R7      :R7=#0206.
0047 F7                 BNZ     POS
0048                    GHI     R5      :CHANGE VALUE AT #020C.
0048 17                 STR     R9      :TO #00.
0049                    OUT     1       :O P #7E: CLICK BASELINE.
0049 3A
004B 4F
004C                    LDI     0#08
004C F8
004D 08
004E                    PLO     R10     :SET R8.0 TO #08.
004E A8
004F                    LDI     0#80
004F F8
0050 80
0051                    PHI     R3      :SET R3.1 TO #80.
0051 B3
0052                    GHI     R3
0052 93
0053                    PLO     R11     :SET R3.0 TO #80.
0053 A3
0054                    BR      MIA
0054 30
0055 5E
0056                    NOP
0056 C4
0057                    NOP
0057 C4
0058                    NOP
0058 C4
0059                    NOP
0059 C4
005A                    LDI     0#A0
005A F8
005B A0
005C                    PLO     R8      :SET R8.0 TO #A0.
005C A8
005D                    INC     R8
005D 18
005E                    PLO     R3      :SET R3.0 TO #A0.
005E A3
005F                    SEX     R9

                *       GENERATION OF CLICKS.

0060                    OUT     1       :OUTPUT #FF TO #00.
0060 61

                *       CLICK WIDTH DELAY=100 US.

0061                    LDI     0#05
0061 F8
0062 05
0063                    PLO     R6      :SET R6.0 TO #05.
0063 A6
0064                    DEC     R6
0064 26
0065                    GLO     R6
0065 86
0066                    BNZ     WID
```

```
006A  3A
006B  6B
006C                    DEC     R7      :R7=#0206.
006C  27
006D                    SEX     R7
006D  E7
006E                    OUT     1       :OUTPUT #7E.
006E  61

                *       AVERAGE ROUTINE.

                *       READ AND ADD DATA.

006F            AVE     INP     2       :READ DATA FROM A-D
006F  6A
0070                    SEX     R9      :CONVERTER AND START
0070  E9
0071                    ADD             :NEW CONVERSION.
0071  F4
0072                    STR     R9
0072  59
0073                    IRX
0073  60
0074                    GHI     R5      :LOAD #00 IN D.
0074  95
0075                    ADC
0075  74
0076                    STR     R9
0076  59
0077                    IRX
0077  60
0078                    GHI     R5
0078  95
0079                    ADC
0079  74
007A                    STR     R9
007A  59
007B                    IRX
007B  60
007C                    NOP             :ADJUST TIME BETWEEN
007C  C4
007D                    NOP             :READINGS TO 100US.
007D  C4
007E                    DEC     R8
007E  28
007F                    GLO     R8
007F  88
0080                    SEX     R7
0080  E7
0081                    BNZ     AVE     :GO BACK 160 TIMES.
0081  3A
0082  6F
0083                    LDI     0#08
0083  F8
0084  08
0085                    PLO     R9
0085  A9
0086                    GHI     R7
0086  97
0087                    PHI     R9      :SET R9 TO #0208.
0087  B9
0088                    SEX     R9
0088  E9
0089                    GLO     R12     :LOAD F4,F8 IN #0206.
0089  8C
008A                    STR     R9
008A  59
008B                    GLO     R5
008B  85
008C                    PLO     R14     :RE.0=#00.
008C  AE
008D                    LDI     0#F1
008D  F8
008E  F1
```

```
                *       DELAY TO ADJUST CLICK
                *       PERIOD.

008F            DEL     PLO     R6      :INITIALIZE R6.0.
008F A6
0090            GRA     GLO     R6
0090 86
0091                    PLO     R8
0091 A8
0092            PEQ     DEC     R8
0092 28
0093                    GLO     R8
0093 88
0094                    BNZ     PEQ
0094 3A
0095 92
0096                    DEC     R6
0096 26
0097                    GLO     R6
0097 86
0098                    BNZ     GRA
0098 3A
0099 90
009A                    LDI     0#04
009A F8
009B 04
009C                    SD
009C F5
009D                    BZ      DE1
009D 32
009E 35
009F                    GLO     R5
009F 85
00A0                    SD
00A0 F5
00A1                    DEC     R6
00A1 26
00A2                    BZ      DE3
00A2 32
00A3 AD
00A4                    LDX
00A4 F0
00A5                    SHR
00A5 F6
00A6                    NOP
00A6 C4
00A7                    NOP
00A7 C4
00A8                    STR     R9
00A8 59
00A9                    LDI     0#ED
00A9 F8
00AA ED
00AB                    BR      DEL
00AB 30
00AC 8F
00AD            DE3     DEC     R14
00AD 2E
00AE                    GLO     R14
00AE 8E
00AF                    BZ      DE2
00AF 32
00B0 B5
00B1                    LDI     0#ED
00B1 F8
00B2 ED
00B3                    BR      DEL
00B3 30
00B4 8F
00B5            DE1     INC     R8
00B5 18
00B6            DE2     SEX     R7
00B6 E7
00B7                    INC     R9      :SET R9 TO #0205.
00B7 19
00B8                    DEC     R7
00B8 27
00B9                    DEC     R7      :SET R7 TO #0205.
00B9 27
```

```
0089
008A 90                GHI     R12     :LOAD #00 INTO D.
008B                   SD              :SUBTRACT #FF-#01.
008B FD
008C                   BNZ     SAM     :TEST FOR ALTERNATE
008C 9A                                :CLOCK GENERATION.
008D
008E 09                LDN     R9
008F                   NOP
008F C4
0090                   NOP
0090 C4
0091                   BNZ     NEG
0091 3A
0092 C8
0093                   LDI     0#FF    :STORE #FF IN #020C.
0093 F8
0094 FF
0095                   STR     R9
0095 59
0096                   BR      DIF
0096 30
0097 D2
0098           NEG     GHI     R5
0098 95
0099                   STR     R9      :STORE #00 IN #020C.
0099 59
009A                   BR      DIF
009A 30
009B D2
009C           SAM     GHI     R7
009C 97
009D                   PLO     R6      :R6.0=#02.
009D A6
009E           DSA     DEC     R6
009E 26
009F                   GLO     R6
009F 86
00A0                   BNZ     DSA
00A0 3A
00A1 CE
00A2           DIF     INC     R7
00A2 17
00A3                   INC     R7      :SET R7 TO #0207.
00A3 17
00A4                   DEC     R11
00A4 2B
00A5                   GLO     R11
00A5 8B
00A6                   BNZ     QUI
00A6 3A
00A7 5A
00A8                   DEC     R10
00A8 2A
00A9                   GLO     R10
00A9 8A
00AA                   BNZ     MIL     :GO BACK 1024 TIMES.
00AA 3A
00AB 56
00AC                   GLO     R5
00AC 85
00AD                   PLO     R9
00AD A9
00AE                   LDN     R9      :R9=#0203.
00AE 09
00AF                   BZ      POI     :HAS "TIMES*4" BEEN
00AF 32
00B0 F3
00B1                   INC     R7      :REQUESTED?
00B1 17
00B2                   INC     R7
00B2 17
00B3                   INC     R7      :R7=#0204.
00B3 17
00B4                   LDI     0#04
00B4 F8
00B5 04
00B6
00B6                   SD              :SUBTRACT M(R7)-#04.
00B6 F5
```

```
00E7                    DEC     R7
00E7  27
00E8                    DEC     R7
00E8  27
00E9                    DEC     R7      :R7=#02D7.
00E9  27
00EA                    BNZ     FDT
00EA  3A
00EB  F3
00EC                    GHI     R5
00EC  95
00ED                    STR     R9
00ED  59
00EE                    LDI     0#0C
00EE  F8
00EF  0C
00F0                    PLO     R9      :R9=#02D0C.
00F0  A9
00F1                    BR      DMI
00F1  30
00F2  50

                *       SHIFT DATA AND SEARCH FOR
                *       OPTIMUN VALUES FOR DISPLAY

00F3            FDT     INC     R7
00F3  17
00F4                    OUT     4       :LED TIMER* ON.
00F4  64
00F5                    SEX     R9
00F5  E9
00F6                    INC     R7
00F6  17
00F7                    LDN     R7
00F7  07
00F8                    PLO     R6
00F8  A6
00F9            PER     GLO     R3
00F9  83
00FA                    PLO     R10     :SET RA.0 TO #A0.
00FA  AA
00FB                    LDI     0#10
00FB  F8
00FC  10
00FD                    PLO     R9      :R9=#0210.
00FD  A9
00FE            SHI     LDN     R9      :M(R9) INTO D.
00FE  09
00FF                    SHL             :SHIFT D LEFT.
00FF  FE
0100                    INC     R9      :R9+1.
0100  19
0101                    LDN     R9      :M(R9) INTO D.
0101  09
0102                    SHLC            :SHIFT D LEFT WITH CARRY.
0102  7E
0103                    STR     R9      :STORE IN M(R9).
0103  59
0104                    INC     R9      :R9+1.
0104  19
0105                    LDN     R9      :M(R9) INTO D.
0105  09
0106                    SHLC            :SHIFT D LEFT WITH CARRY.
0106  7E
0107                    STXD            :STORE D INTO M(R9) , R9-.
0107  73
0108                    DEC     R9      :R9-1.
0108  29
0109                    LDN     R9      :M(R9) INTO D.
0109  09
010A                    SHLC            :SHIFT D LEFT WITH CARRY.
010A  7E
010B                    STR     R9      :STORE D IN M(R9).
010B  59
010C                    INC     R9
010C  19
010D                    INC     R9
010D  19
```

```
010E                    INC     R9      :R9=#03E9.
010E  19
010F                    DEC     R10
010F  2A
0110                    GLO     R10
0110  8A
0111                    LBNZ    SHI     :DO IT 160 TIMES.
0111  CA
0112  00FE
0114                    SQ      PAS
0114  31
0115  13
0115                    DEC     R6
0116  26
0117                    GLO     R6
0117  86
0118                    BNZ     REP
0118  3A
0119  35
011A                    SKP
011A  38
011B            PAS     REQ             :RESET Q.
011B  7A
011C                    LDI     0#95
011C  F8
011D  95
011E                    PLO     R6      :SET R6.0 TO #95.
011E  A6
011F                    DEC     R7      :R7=#0209.
011F  27
0120                    DEC     R9      :R9=#03FE.
0120  29
0121                    GHI     R3      :LOAD #80 INTO D.
0121  93
0122                    AND             :AND M(03FE) WITH #80.
0122  F2
0123                    STR     R7      :STORE IN #0209.
0123  57
0124            OTR     DEC     R9      :R9-1.
0124  29
0125                    DEC     R9      :R9-1.
0125  29
0126                    DEC     R9      :R9-1.
0126  29
0127                    GHI     R3      :LOAD #80 INTO D.
0127  93
0128                    AND             :AND D WITH M(R9).
0128  F2
0129                    SEX     R7
0129  E7
012A                    ADD             :ADD D WITH M(R7).
012A  F4
012B                    SEX     R9
012B  E9
012C                    BNZ     FDS
012C  3A
012D  3A
012E                    DEC     R6
012E  26
012F                    GLO     R6
012F  86
0130                    BNZ     OTR
0130  3A
0131  24
0132                    SEQ             :SET Q.
0132  7B
0133                    INC     R2      :R2+1.
0133  12
0134                    INC     R7      :R7=#020A.
0134  17
0135            REP     GHI     R7
0135  97
0136                    PHI     R9      :R9.1=#02.
0136  B9
0137                    LBR     PER
0137  C0
0138  00F9
013A            FDS     SEX     R7
013A  E7
013B                    GHI     R7
```

```
0162                    STR     R7
0162  57
0163                    OUT     4       :SWITCH MOTOR ON.
0163  64

                *       DELAY TO RUN MOTOR FOR  2 MS BEFORE
                *       PRINTING THE RESPONSE.

0164                    LDI     0#D2
0164  F8
0165  D2
0166                    PLO     R8      :R8.0=D2
0166  A8
0167                    PHI     R8      :R8.1=D2
0167  B8
0168            PRI     DEC     R8
0168  28
0169                    GLO     R8
0169  88
016A                    BNZ     PRI
016A  3A
016B  68
016C                    GHI     R8
016C  98
016D                    BNZ     PRI
016D  3A
016E  68
016F                    BR      EMP     :BRANCH TO DISPLAY ROUTINE
016F  30
0170  7C

                *       TRIGGER PULSE GENERATION.

0171            NPR     LDI     0#40
0171  F8
0172  40
0173                    ADD
0173  F4
0174                    STR     R7
0174  57
0175                    OUT     4
0175  64
0176                    DEC     R7
0176  27
0177                    NOP
0177  C4
0178                    ADI     0#C0
0178  FC
0179  C0
017A                    STR     R7
017A  57
017B                    OUT     4
017B  64
017C            EMP     SEX     R9
017C  E9

                *       DISPLAY ROUTINE.

017D            FUL     OUT     1
017D  61
017E                    IRX             :R9+1.
017E  60
017F                    IRX             :R9+1.
017F  60
0180                    LDI     0#06
0180  F8
0181  06
0182                    PHI     R8      :R8.1=#06.
0182  B8
0183                    BNQ     DSC     :GO TO DSC IF NO PRINTING
0183  39
0184  8F
0185                    LDI     0#FA    :REQUESTED.
0185  F8
```

```
0186  FA
0187                    PLO     R8      :R8.0=#FA.
0187  A8

                *       PRINT DELAY  25 MS.

0188            DEP     DEC     R8
0188  28
0189                    GLO     R8
0189  88
018A                    BNZ     DEP
018A  3A
018B  8B
018C                    GHI     R8
018C  98
018D                    BNZ     DEP
018D  3A
018E  8B

                *       OSC. DISPLAY DELAY  50 MS.

018F            OSC     GLO     R5
018F  85
0190                    PLO     R8      :R8.0=#03.
0190  A8
0191            RTI     DEC     R8
0191  28
0192                    GLO     R8
0192  88
0193                    BNZ     RTI
0193  3A
0194  91
0195                    DEC     R10
0195  2A
0196                    GLO     R10
0196  8A
0197                    BNZ     FOL     :GO TO FOL 160 TIMES.
0197  3A
0198  70
0199                    GHI     R7
0199  97
019A                    PHI     R9
019A  B9
019B                    LDI     0#12
019B  F8
019C  12
019D                    PLO     R9      :R9=#0212.
019D  A9
019E                    SEX     R7
019E  E7
019F                    BNQ     TES     :IF PRINTING CONTINUE,
019F  39
01A0  81
01A1                    DEC     R7      :ELSE GO TO TES.
01A1  27
01A2                    REQ
01A2  7A
01A3                    LDI     0#10
01A3  F8
01A4  10
01A5                    SD
01A5  F5
01A6                    STR     R7
01A6  57
01A7                    OUT     4       :SWITCH OFF STYLUS HEATER.
01A7  64
01A8                    LDI     0#07
01A8  F8
01A9  07
01AA                    BR      MOI     :GO TO MTOP DELAY.
01AA  30
01AB  4D
01AC            R4D     LDI     0#08
01AC  F8
01AD  08
01AE                    SD
```

```
01AE  F5
01AE
01AF  57                STR     R7
01B0                    OUT     4       :SWITCH OFF MOTOR.
01B0  64
01B1          TES       INC     R7
01B1  17
01B2                    LDI     0#04
01B2  F8
01B3  04
01B4                    SD
01B4  F5
01B5                    DEC     R7
01B5  27
01B6                    BZ      DIS     :IF TIMES*4 DONE, GO BACK
01B6  32
01B7  40
01B8                    BN4     DIS     :TO DISPLAY ROUTINE, ELSE
01B8  3F
01B9  40
01BA                    NOP             :TEST FLAG 4. IF ON CONTIN
01BA  C4
L             *                         :ELSE, GO TO DISPLAY.

              *         SHIFT DATA TO ITS ORIGINAL
              *         POSITION.

01BB                    INC     R7
01BB  17
01BC                    GLO     R2
01BC  82
01BD                    ADD
01BD  F4
01BE                    PLO     R2      :SET R2.0 TO THE NUMBER
01BE  A2
01BF                    SEX     R9      :OF RIGHT SHIFTS.
01BF  E9
01C0          SBA       GLO     R3
01C0  83
01C1                    PLO     R10     :RA.0=#A0.
01C1  AA
01C2          CDS       LDN     R9      :LOAD M(R9) INTO D.
01C2  09
01C3                    SHR             :SHIFT D RIGHT.
01C3  F6
01C4                    DEC     R9      :R9-1.
01C4  29
01C5                    LDN     R9      :LOAD M(R9) INTO D.
01C5  09
01C6                    SHRC            :SHIFT D RIGHT WITH CARRY.
01C6  76
01C7                    STXD            :STORE D IN M(R9), R9-1.
01C7  73
01C8                    LDN     R9      :LOAD M(R9) INTO D.
01C8  09
01C9                    SHRC            :SHIFT D RIGHT WITH CARRY.
01C9  76
01CA                    STR     R9      :STORE D IN M(R9).
01CA  59
01CB                    INC     R9      :R9+1.
01CB  19
01CC                    INC     R9      :R9+1.
01CC  19
01CD                    LDN     R9      :LOAD M(R9) INTO D.
01CD  09
01CE                    SHRC            :SHIFT D RIGHT WITH CARRY.
01CE  76
01CF                    STR     R9      :STORE D IN M(R9).
01CF  59
01D0                    INC     R9      :R9+1.
01D0  19
01D1                    INC     R9      :R9+1.
01D1  19
01D2                    INC     R9      :R9+1.
01D2  19
01D3                    DEC     R10
01D3  2A
01D4                    GLO     R10
```

```
0138  97                PHI     R9
013C                    LDI     0#12
013C  B9
013D  F8
013E  12
013F                    PLO     R9      :SET R9 TO #0212.
013F  A9
0140          DIS       GLO     R3
0140  83
0141                    PLO     R10     :RA.0=#A0.
0141  AA
0142                    DEC     R7      :R7=#0209.
0142  27

              *         TEST FLAG N3, IF ON A PRINT IS DONE.
              *         AND Q IS SET.

0143                    BN3     NPR
0143  3E
0144  71
0145                    SEQ             :SET Q.
0145  7B
0146                    LDI     0#10
0146  F8
0147  10
0148                    ADD
0148  F4
0149                    STR     R7
0149  57
014A                    OUT     4       :TURN HEATER STYLUS ON.
014A  64

              *         DELAY TO BE USED FOR HEATER STYLUS
              *         AND MOTOR AFTER PRINTING.

0143                    LDI     0#15
0143  F8
0144  15
0145          MOI       PLO     R8      :INITIALIZE R8.0.
0145  A8
014E                    DEC     R7
014E  27
014F          HE1       GLO     R3
014F  83
0150                    PLO     R6      :R6.0=#A0.
0150  A6
0151                    PHI     R6      :R6.1=#A0.
0151  B6
0152          HE2       DEC     R6
0152  26
0153                    GLO     R6
0153  86
0154                    BNZ     HE2
0154  3A
0155  52
0156                    GHI     R6
0156  96
0157                    BNZ     HE2
0157  3A
0158  52
0159                    DEC     R8
0159  28
015A                    GLO     R8
015A  88
015B                    BNZ     HE1
015B  3A
015C  4F
015D                    BNQ     RMO
015D  39
015E  AC
015F                    LDI     0#08
015F  F8
0160  08
0161                    ADD
0161  F4
```

```
0104  3A
0105                    BNZ     CDS     :REPEAT IT 160 TIMES.
0105  C2
0106
0107  97                GHI     R7
0108                    PHI     R9
0108  B9
0109                    LDI     0#12
0109  F8
010A  12
010B                    PLO     R9      :SET R9 TO #0212.
010B  A9
010C                    DEC     R2      :R2-1.
010C  22
010D                    GLO     R2
010D  82
010E                    BNZ     SBA
010E  3A
010F  C0

                *       THE CONTROLS ARE SET BEFORE STARTING
                *       THE NEW 1024 CLICKS GENERATION.

01E0                    SEX     R7
01E0  E7
01E1                    GHI     R12
01E1  9C
01E2                    SD
01E2  F5
01E3                    STXD
01E3  73
01E4                    GHI     R5
01E4  95
01E5                    STR     R7
01E5  57
01E6                    OUT     4       :SWITCH OFF THE TIMES*N LE
01E6  64
01E7                    DEC     R7
01E7  27
01E8                    DEC     R7
01E8  27
01E9                    LDI     0#0F
01E9  F8
01EA  0F
01EB                    AND
01EB  F2
01EC                    SHL
01EC  FE
01ED                    STR     R7      :STORE IN #0208 DATA FOR
01ED  57
01EE                    LDI     0#20    :PEN REG. AND LEDS CONTRO
01EE  F8
01EF  20
01F0                    ADD
01F0  F4
01F1                    STXD
01F1  73
01F2                    DEC     R7      :SET R7 TO #0206.
01F2  27
01F3                    LDI     0#0C
01F3  F8
01F4  0C
01F5                    PLO     R9      :SET R9 TO #020C.
01F5  A9
01F6                    LBR     PDS     :GO TO PDS.
01F6  C0
01F7  004F
01F9                    IDL
01F9  C0
01FA                    IDL
01FA  00
01FB                    IDL
01FB  C0
01FC                    IDL
01FC  C0
01FD                    END
```

4070U5 C4 STORAGE USED 1287 STATEME
MODEL 174 ASSEMBLY 8.709 SECONDS

SYMBOLIC REFERENCE TABLE.

AVE	197		4/19	L	4/55			
CLEEL	22		1/59	L	2/09			
CLEE2	25		1/74	L	2/02			
CUS	702		12/44	L	13/02			
DDEEL	217		5/05	L	5/09		5/68	
DDEEP	810		11/09	L	11/13		11/18	
DEE1	255		5/30		5/71	L		
DEE2	266		5/52		5/73	L		
DEE3	255		5/39		5/58	L		
DIFF	322		6/22		6/24		6/43	L
DIS	900		9/09	L	12/15		12/18	
DMI	120		3/23	L	7/19			
DSA	310		6/36	L	6/40			
EMP	574		10/30		10/58	L		
FDL	979		10/05	L	11/41			
FDS	472		8/05		8/78	L		
FDT	363		6/57		7/07		7/28	L
GRA	220		5/07	L	5/22			
HEE1	517		9/48	L	9/70			
HEE2	522		9/54	L	9/58		9/63	
MIA	135		3/37		3/48	L		
MIL	129		3/33	L	6/98			
MOI	915		9/44	L	11/74			
NEG	310		6/14		6/20	L		
NPR	961		9/21		10/58	L		
OSC	817		10/76		11/20	L		
OTR	444		8/39	L	8/62			
PAS	433		8/10		8/22	L		
PEQ	222		5/11	L	5/15			
PER	371		7/40	L	8/75			
PUS	117		3/14		3/21	L	13/68	
PRI	900		10/18	L	10/22		10/27	
RDI	132		8/40	L	8/51			
REP	466		8/17		8/71	L		
RMU	654		9/73		11/77	L		
RTI	821		11/30	L	11/34			
SAM	314		6/05		6/32	L		
SBA	700		12/40	L	13/18			
SHI	376		7/49	L	8/07			
TES	661		11/55		12/06	L		
WID	190		3/76	L	4/80			

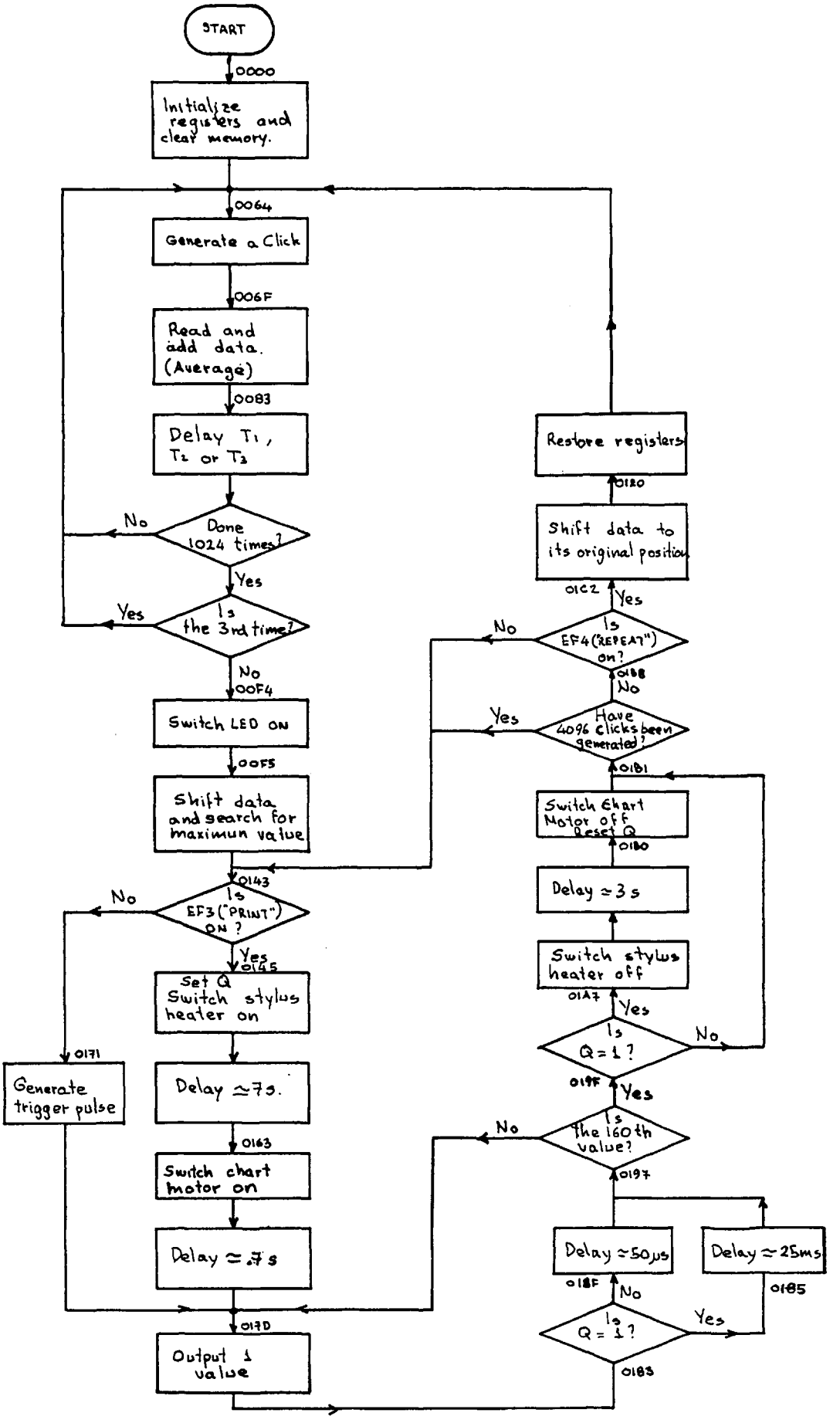


Fig. A.1. BSER Audiometer software flow diagram (Numbers refer to address of start of each routine).

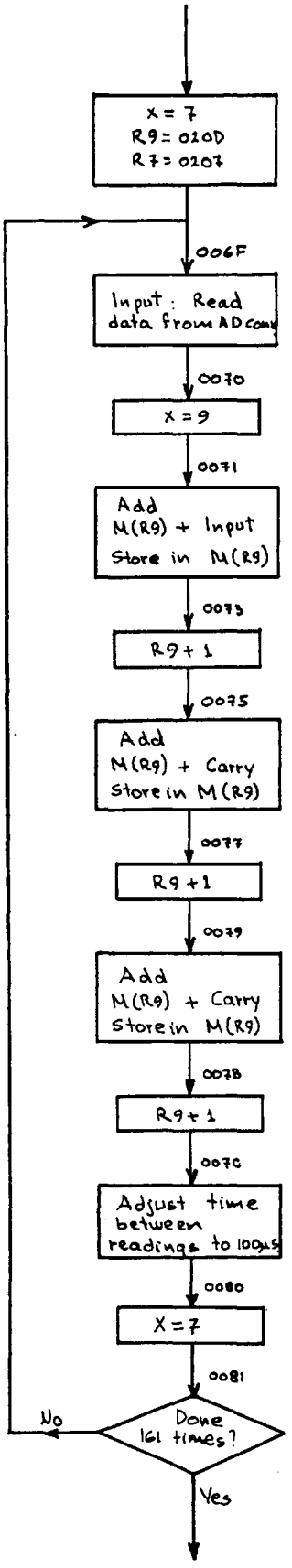


Fig. A.2 Read and add data flow diagram.

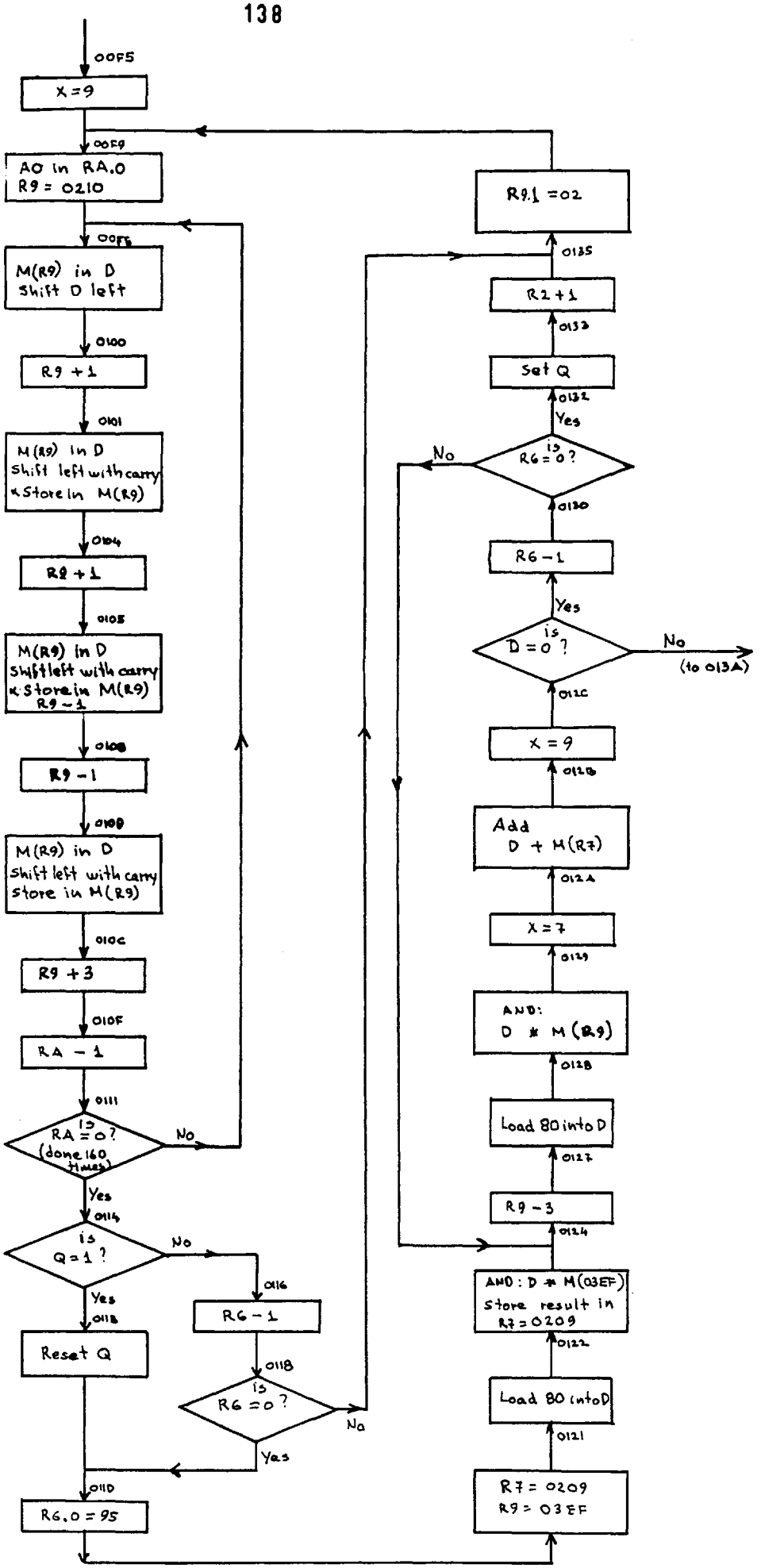


Fig. A.3 Shift and search flow diagram.

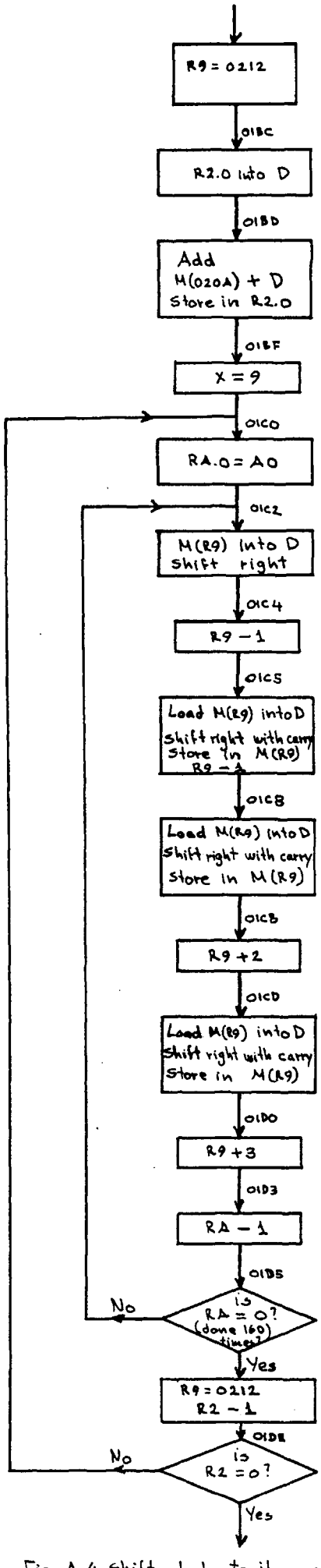


Fig. A.4 Shift data to its original position flow diagram

APPENDIX B

CIRCUIT DIAGRAMS

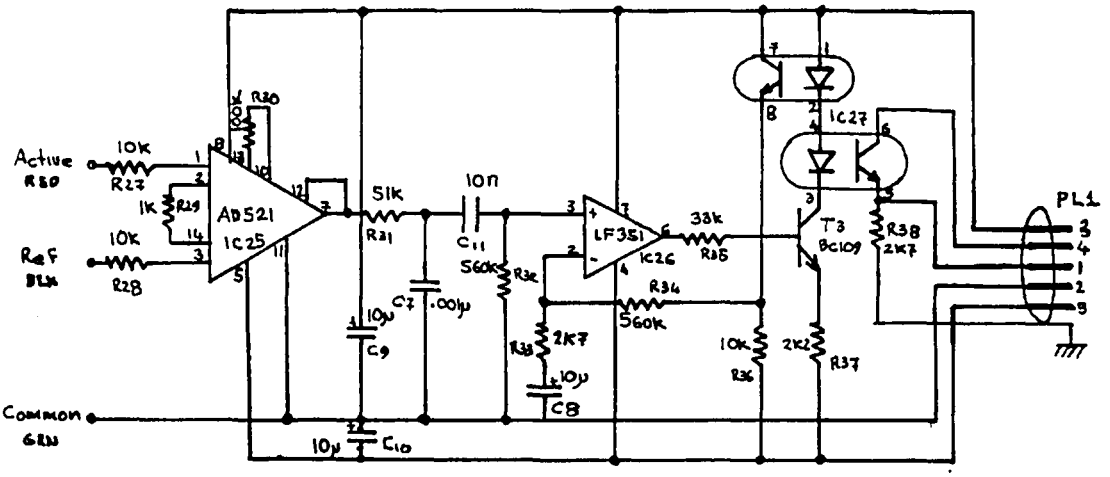
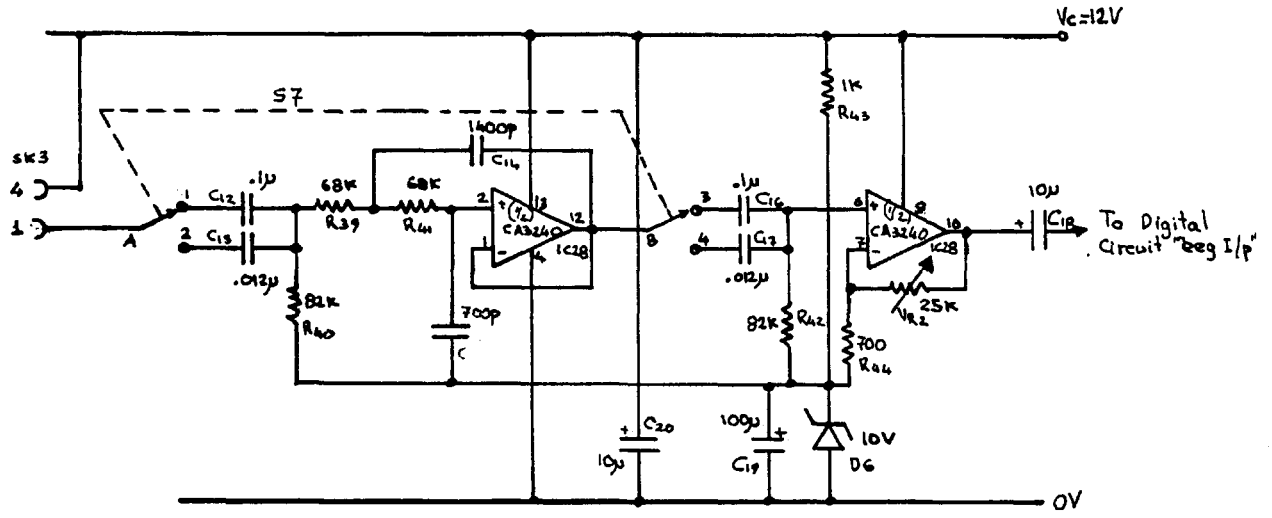


Fig. B.2 Preamplifier



S7 : "FILTER Fco"

VR2 : "GAIN"

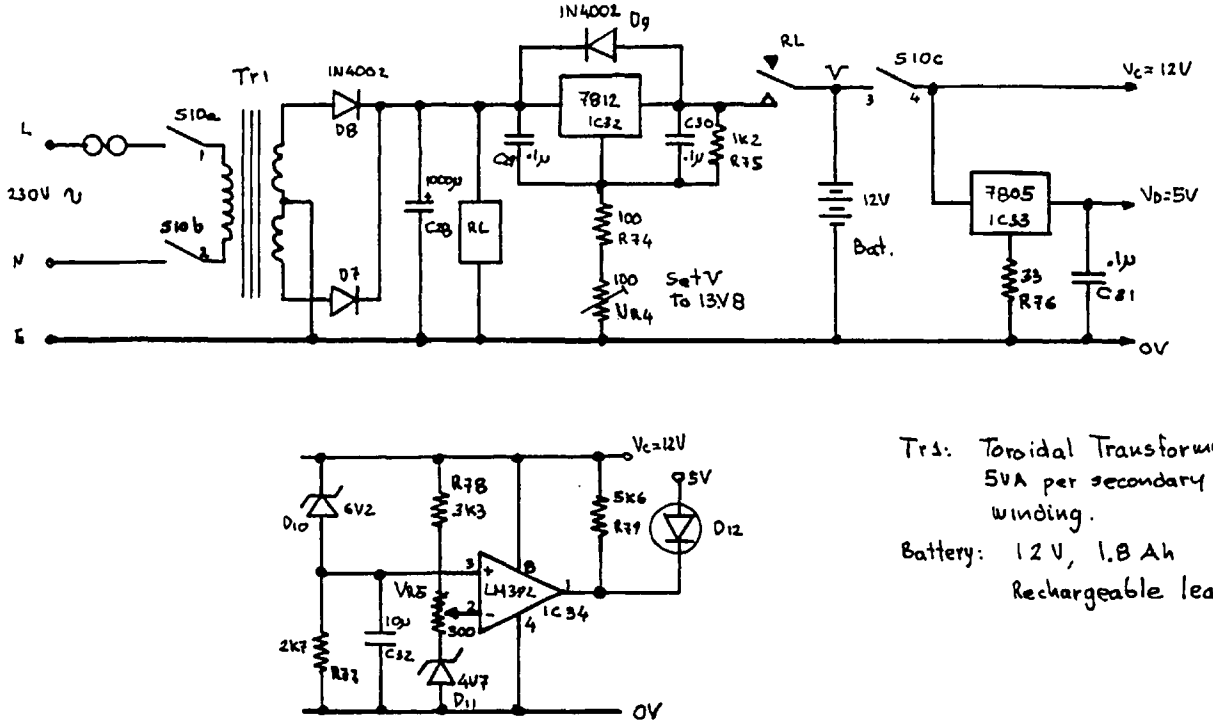
Fig. B.3. Amplifier and Filters

Fig. B.1. Digital Circuit

$V_D = 5V$

$V_C = 12V$

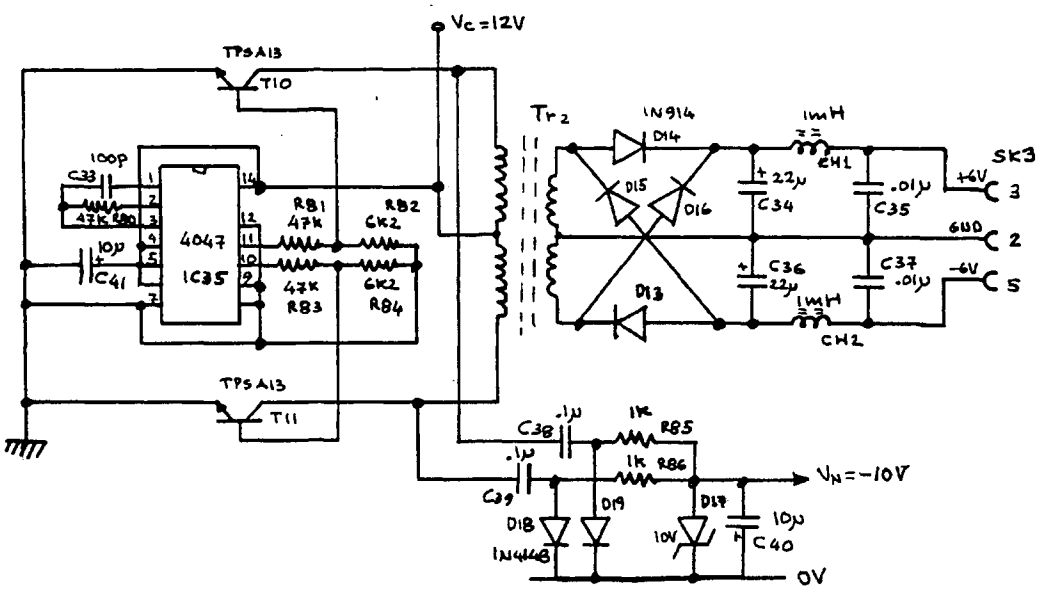
- Switches
  - S1 : Front pannel "START"
  - S2 : " " "RESET"
  - S3 : " " "PRINT"
  - S4 : " " "REPEAT"
  - S5 : " " "POLARITY"
  - S6 : " " "CLICK FREQ. Hz"
- Diodes
  - D1 "RESET" Led
  - D2 "x1" "
  - D3 "x2" "
  - D4 "x4" "
- Potentiometers
  - VR1 Shift "↔" Knob
- Sockets
  - SK1 "TRIGGER" Socket
  - SK2 "MONITOR" "



Tr1: Toroidal Transformer
5VA per secondary winding.
Battery: 12V, 1.8 Ah
Rechargeable lead-acid

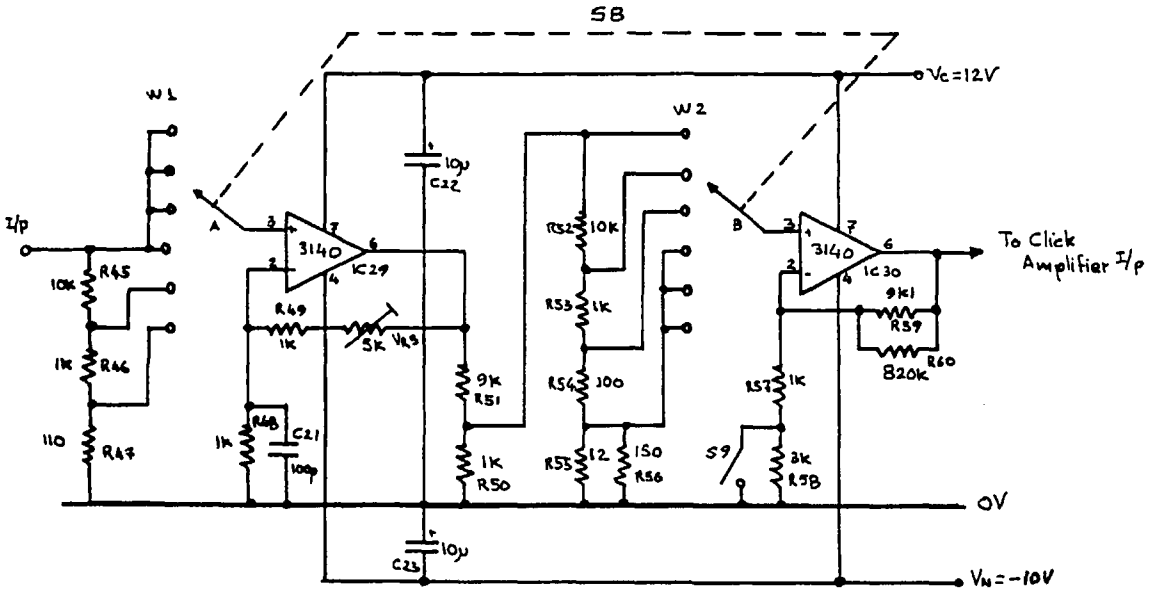
D12 : "BATT. LOW" Led.

Fig. B.6. Power Supply and "Battery Low" Alarm



Tr2: Toroid FX3313
Primary turns 80 SWG30
Secondary turns 47 SWG30

Fig B.7 DC-DC Converter

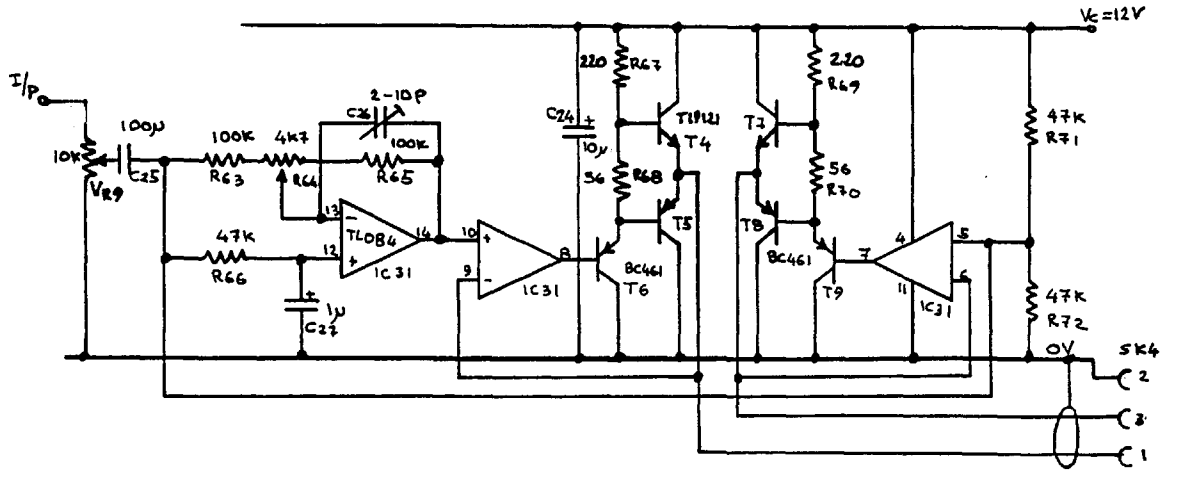


SB: "AMPLITUDE dB"

S9: " -10dB"

VR3 "SET 100 dB"

Fig. B.4. Click Attenuator



SK4: "OUTPUT" Earphones socket

Fig. B.5. Click Amplifier

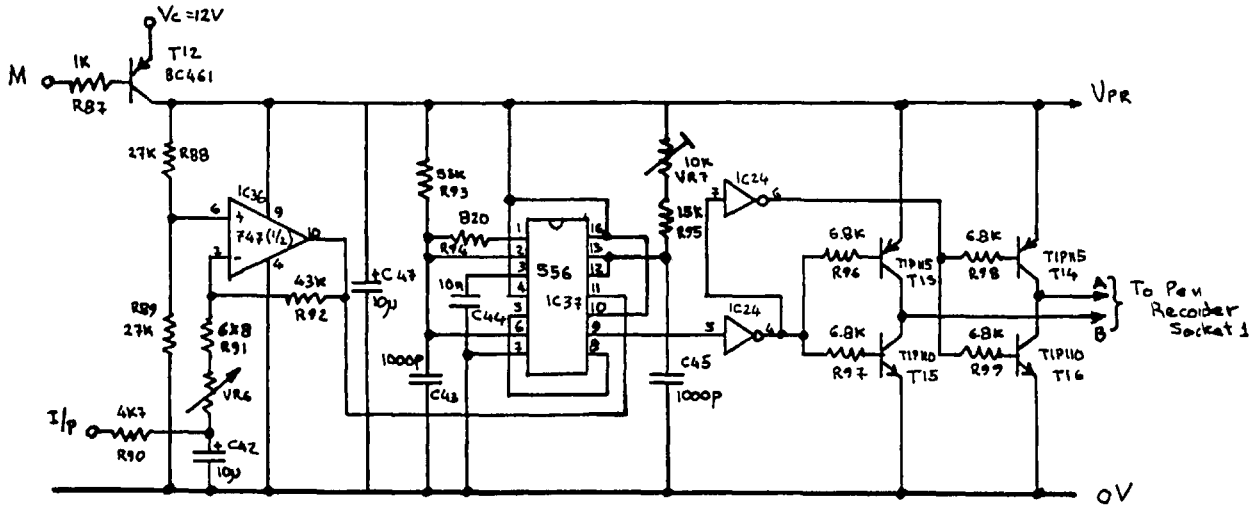
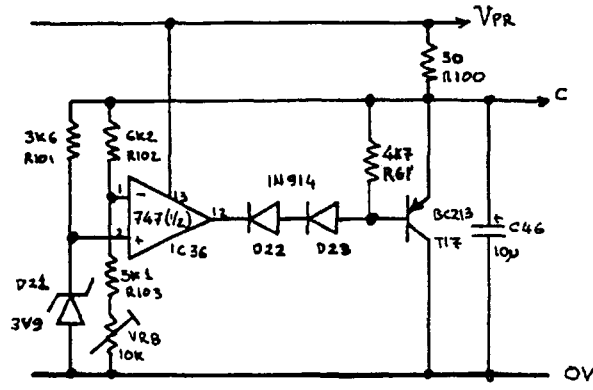


Fig. B8 Stylus Deviation

V_{RG}: "Trace Amplitude" knob.



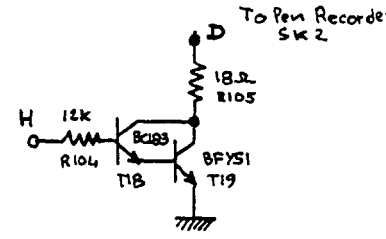


Fig. B.10 Stylus Heater

Fig. B.9 Chart Motor Control

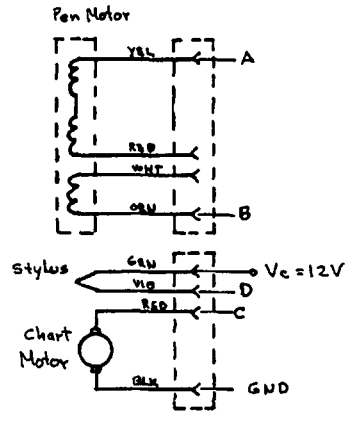


Fig. B.11 Pen Recorder Connections

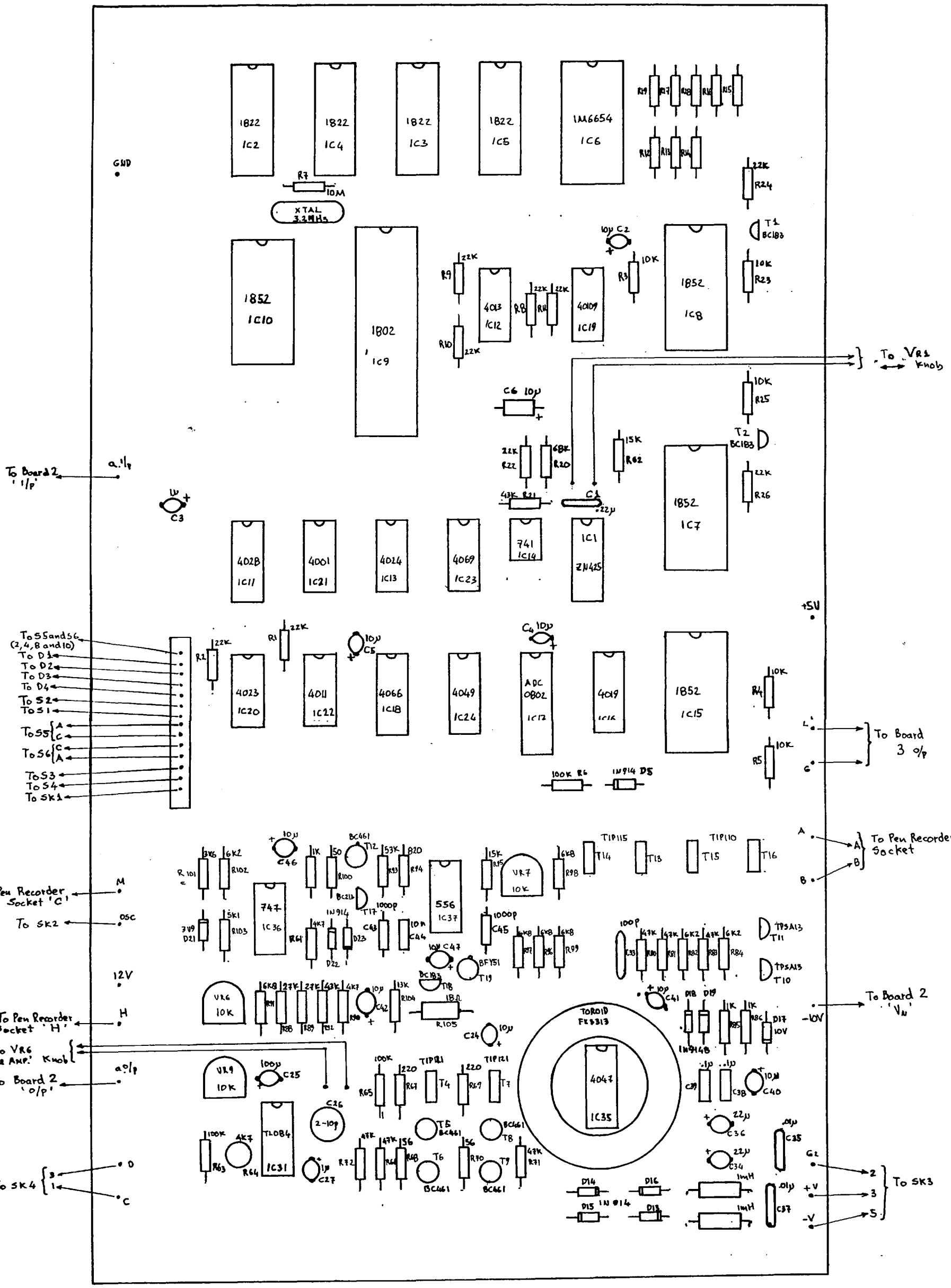


Fig.B.8 Board 1 Layout

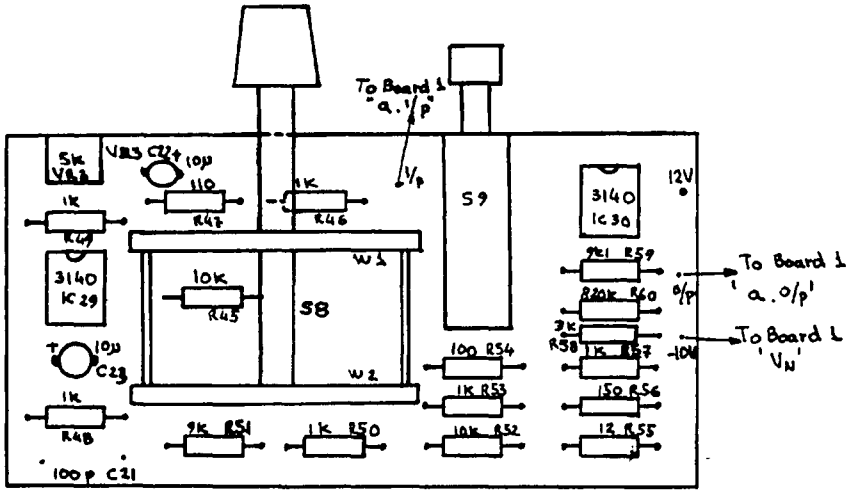


Fig. B.9. Board 2 Layout

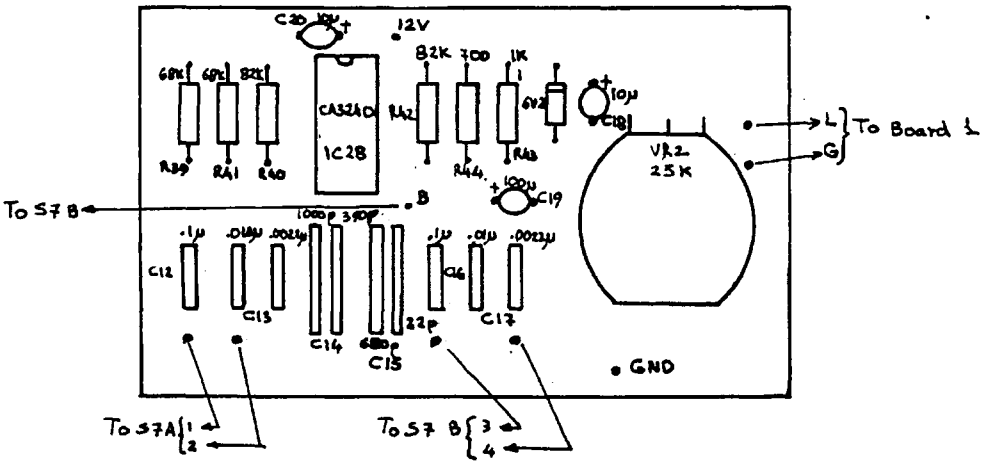


Fig. B.10 Board 3 Layout

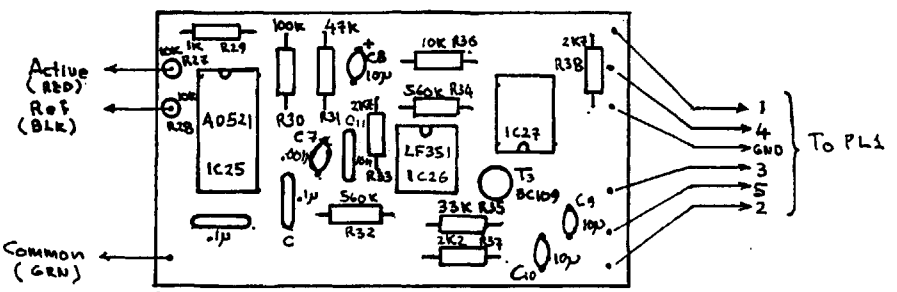


Fig. B.11 Board 4 Layout.

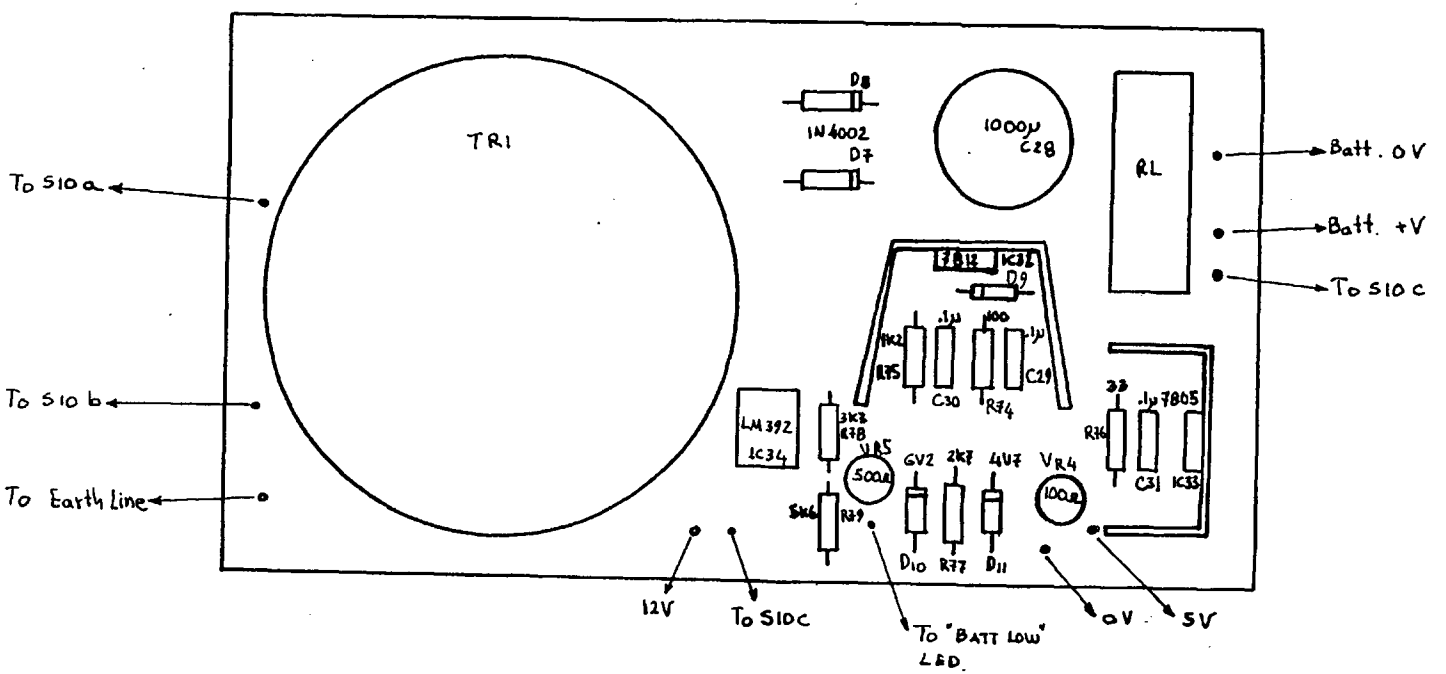


Fig. B.12 Board 5 Layout

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