Dynamic Aspects of Perception in Binaural Listening

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by

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ABSTRACT

A computer monitored binaural centring experiment technique is employed to investigate the effects of repeated presentations of binaurally unbalanced acoustic stimuli. It is found that in these circumstances a form of adaptation occurs having a time constant of some 80 seconds.

The origin of this effect, labelled binaural adaptation, is discussed and it is argued that a centrally controlled middle-ear muscular activity is most likely to be responsible for the phenomenon.

The listener's responses are compared to the behaviour predicted by a recently formulated model of binaural interaction that considers the important inner-ear peripheral transformations of the acoustic signal. It is found that the model is capable of predicting accurately the observed behaviour, especially by drawing attention to the importance of multiple coexisting images and in accounting for the listener's perception of these images. This particular perceptual situation is found to occur with the binaural interaction of simple transients with inter-aural amplitude difference as well as with more complex pulse pattern presentations.

It is found in this context that binaural adaptation is related to the perception of multiple images; because of this fact, adaptation can be interpreted as a progressive shift of attention from one image to another. In the case of the interaction of complex transients (single pulse versus contralateral double pulse interaction) it is found that this behavioural effect can be

mediated by a middle ear muscular activity that results in a substantial alteration of the neural coding of the acoustic stimulus.

In the course of this work, the frequency response of a human operator in an auditory tracking task of a compensatory type is also investigated. It is found that the operator's function can be represented adequately by a first order low-pass filter system cascaded with an element of pure delay.

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CHAPTER I

INTRODUCTION

This study presents an experimental investigation on certain aspects of binaural fusion, the human capacity that essentially underlies sound localisation and spatial auditory discrimination. It is concerned with two dynamic aspects of binaural perception, namely the perceptual changes associated with the repeated presentations of acoustic stimuli and the perception of moving sound sources.

In essence this work fills an important gap in psycho-acoustic study by considering a new dimension, that of perceptual changes in binaural fusion. More than often the listener's behaviour in binaural experiments is thought of as a static entity; for instance this is done by taking the average of a set of data recorded in succession as that typically representing the behaviour ensemble. At first this may be a valid approach to a quantification of some psycho-physical matter but by no means can it be certain that it is the correct one. Man is in fact continuously adapting to his environment and quite certainly this is true about his perceptual capabilities. Indeed most sensory mechanisms are better at detecting changes and very often fail to their role when subjected to a continuous, stable stimulus.

This property certainly reflects many important aspects inherent to perceptual functions and needs to be considered in the understanding of the relevant mechanism.

The present study investigates dynamic aspects of auditory perception using a psycho-acoustic technique of a lateralization type, where transients are presented through headphones to produce acoustic images perceived intra-cranially. In particular the binaural centring technique is used to observe perceptual behaviours: the subjects are asked to adjust the inter-aural time difference between the binaural signals so as to perceive an acoustic image positioned on an intra-cranial, imaginary, median plane.

More specifically this research investigates the binaural interaction of low-pass filtered (2 khz cut-off frequency) transients presented in selected pulse patterns: simple transients with and without inter-aural amplitude difference (I.A.D.), complex transients used to study backward and forward masking. (double clicks versus single click interaction). The choice of these particular experimental conditions is not arbitrary and is justified by several reasons.

The type of stimulus itself, (acoustic transients), is suggested by the fact that it seems to be particularly suitable to the study of binaural interaction, since it has been observed that localisation of a sharp onset sound source is more easily achieved than continuous tonal one. As far as the low-pass filtering of these stimuli is concerned, this technique has been proposed elsewhere (Toole and Sayers,(1964)) as a possible way of eliminating certain confusing acoustic images. The technique has also a great advantage in that the actual acoustic pressure waveform at the tympanic membrane is less influenced by the multiple reflections produced in the outer-ear headphone cavity, and hence is more predictable.

The pulse patterns (simple transients with I.A.D., complex transients) used in the present study are selected because their associated binaural interaction is thought to be closely related to important neurophysiological mechanisms of auditory perception. The interpretation of the psycho-physical behaviour of listeners subjected to auditory stimulation of that type is still subject to controversy, possibly because changing perceptual behaviours of listeners have not yet been considered. The present research intends to shed some light on this question.

In this study, each type of experiment is carried out with a group of 6 subjects (5 males, 1 female) who were found to have normal hearing after an otological examination that included a Bekesy audiometric test. For a given experiment, a subject is asked to report 128 binaural judgements in one sitting; hence some 768 binaural centring are made available per type of experiment. This procedure ensures within reason that any set of data allows reliable conclusions to be drawn.

A computer monitored technique is developed that enables the large number of judgements that this study necessitates to be collected automatically. The technique consists essentially in linking to a process computer (IBM 1800) a programmable pulse generator specially designed for the purpose of the present research. By eliminating tedious and lengthy adjustments of controls, the technique permits successive presentations of acoustic images to be made rapidly and so enables one to get the most of the usable period of a subject's attention. The method also has the great advantage of offering a tight control of the many experimental parameters thus giving more repetitive results.

This study reports on some 10,000 binaural judgements obtained with this technique.

CHAPTER II

ANATOMY AND PHYSIOLOGY OF HEARING AND THE RELATION TO THE BINAURAL FUSION PROCESS.

II.1 Introduction

This chapter provides a basic anatomical and physiological description of the various elements that ultimately constitute the human sense of hearing. The exposé purposes to outline the important transformations that the anatomical structure imposes on the acoustic signal. Of a particular interest to the present study are the mechanical and neural events occurring in the inner ear.

Additionally, a model of binaural interaction that takes into account the peripheral (neural) coding of the auditory signal, will be briefly discussed: this model, originally presented by Monro, (1971) will in fact be frequently referred to along the course of this work.

II.2 Anatomy of the Ear

II.2.1 Outer and Middle Ear

Figure II.1 illustrates a simplified anatomy of the human ear. Generally speaking the ear is thought of as being divided in three parts: the outer, middle and inner ear.

The outer ear consists of the auricle or pinna, leading to the auditory canal (external meatus) that itself terminates at the tympanic membrane.

> The auditory meatus is simply a slightly curved tunnel through the temporal bone, 25 mm long and a diameter of approximately 1 cm; the tympanic membrane is cone shaped, and lies obliquely across the end of the canal: attached to the wall of the canal by a bony ring, the annulus, it opens to the middle ear.

The middle ear is an air filled mastoidian cavity containing three miniature bones: malleus, incus and stapes. One end of the malleus, the handle or manubrium, is attached to the center of the tympanic membrane, while the other end is bound to the incus; the opposite end of the incus is joined to the stapes in an articulated fashion so that a certain amount of rotation is possible at the incus-stapes interface; the stapes' faceplate lies in the opening of the oval window from which sound is transmitted to the inner ear. Five small ligaments help to support the ossicular system in the cavity; two minute muscles, the stapedius and tensor tympani muscles, are connected to the structure to which their name refers; they contract to protect the inner ear against loud sound exposure. A final structure is connected to the middle ear cavity: the eustachian tube. It consists of a tunnel connecting the pharynx to the cavity so that it is kept at atmospheric pressure.

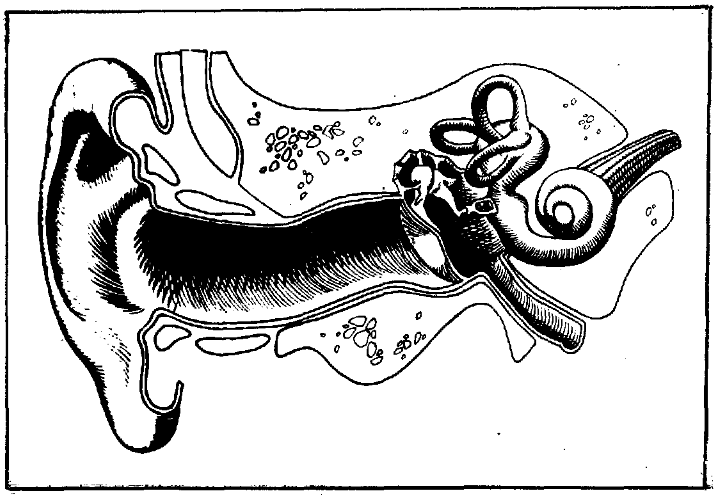

Figure II.1. The ear. From Stevens and Warshofsky (1970).

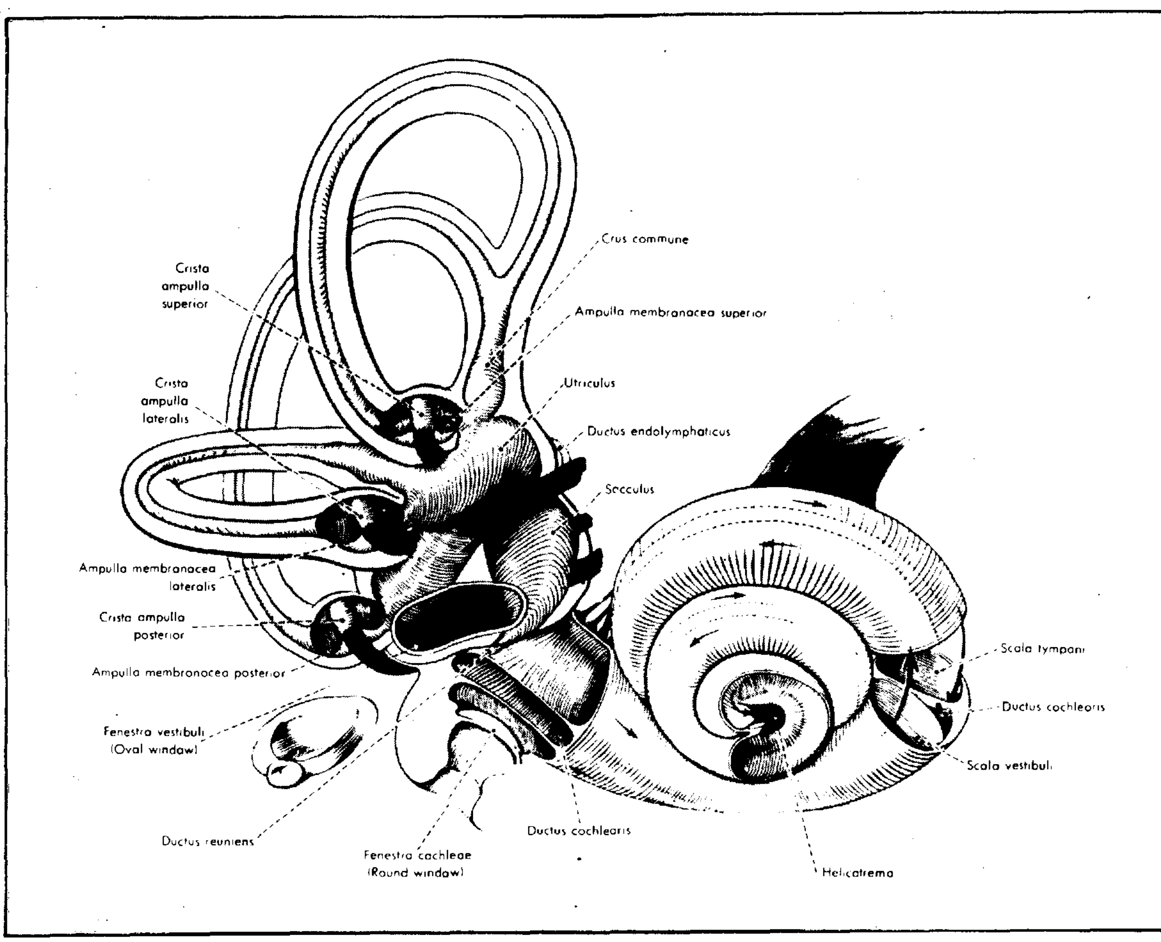

Figure II.2. The inner ear. From Hawkins (1966 A).

II.2.2 The Inner Ear (figure II.2)

The inner ear is embedded in the petrous part of the temporal bone, the thickest and hardest bone of the skull; the bone cavity acts as a shell for the structure and it is referred to as the osseous labyrinth. The inner ear is functionally divided in two parts: the vestibular and auditory apparatus.

> The vestibular apparatus contains the mechanism concerned with the sense of balance: three mutually orthogonal semi-circular canals detect angular acceleration and are partly responsible for the dynamic of equilibrium. The vestibule, the remaining part of the vestibular apparatus, retain the linear acceleration and position sensors.

The inner ear auditory section, the cochlea, is a fluid filled coiled canal.

> Typically the canal, 35 mm long, has a diameter of 3 mm in the first (basal) turn, but narrows progressively towards the apex. The coil would be encompassed by a cone 10 mm in diameter and 5 mm high. This two and three quarter turns helix spirals around a central bony pillar, the modiolus, that itself encloses the auditory nerve. (figure II.3). A bony ledge, the osseous spiral lamina, projects into the canal, winding about the modiolus giving a firm support to the internal structure of the cochlea. The bony lamina is continued to the opposite wall of the cochlear canal by a membranous spiral lamina, the basilar membrane, dividing the cochlear partition in two ducts.

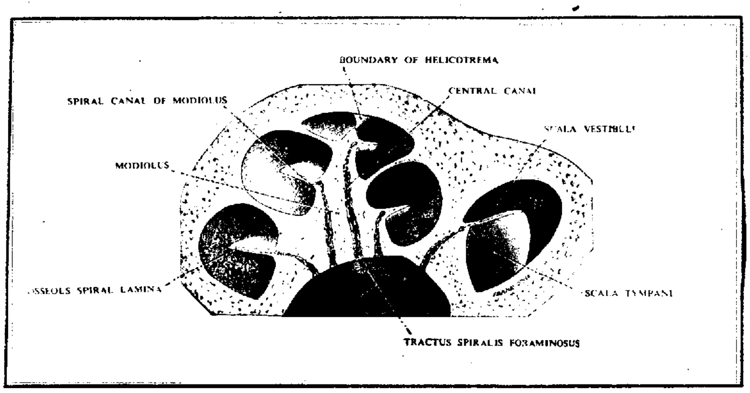

Figure II.3 A Drawing of the Bony Cochlea

From Hamilton, (1966).

A section of the cochlea would however show that in fact there are three distinct scalae (see figure II.2): the scala vestibuli, the scala tympani and the scala media.

> The scala vestibuli is separated from the rest of the cochlear structure by the Reissner membrane, referred also as the vestibular membrane. At the basal end, the scala vestibuli ends in the vestibule at the oval window (fenestra vestibuli) which is closed by the footplate of the stapes. Hence vibrations at the tympanic membrane in the outer ear are transmitted, via the ossicles, to the fenestra vestibuli, setting the fluid in motion in the scala vestibuli.
> At the apex of the cochlea, the scala vestibuli and the scala tympani are in communication through a narrow opening, the helicotrema. The scala tympani is bounded by the osseous labyrinth, by the osseous spiral lamina and the basilar membrane. The scala tympani ends at the round window (fenestra cochleae) covered by a thin membrane, the secondary tympanic membrane.

The basilar membrane is the key structure in the analytic function of the cochlea since the auditory nerve is seen to terminate in association with the cells attached to it. It stretches from the tip of the osseous spiral lamina to a though, dense, fibrous bond called spiral ligament which lines the outer wall of the cochlear canal. The basilar membrane widens from base to apex as opposed to the cochlea that actually tapers in this direction. This, in fact, is due to an apical shortening of the osseous spiral lamina and of the spiral ligament; hence in the lower turn of the cochlea, the membrane is 200μ in breadth while in the apical turn it increases to about 400μ. This tapering ratio of twofolds however shows considerable variation from specimen to specimen. (Wever,(1949))

Together with a set of supporting cells, the Claudius cells, the basilar membrane holds the sensory apparatus: the organ of Corti. (Figure II.4). The spiral organ of Corti consists principally of the tunnel of Corti in the center, with a row of hair cells near the osseous spiral lamina and three rows of hair cells on the

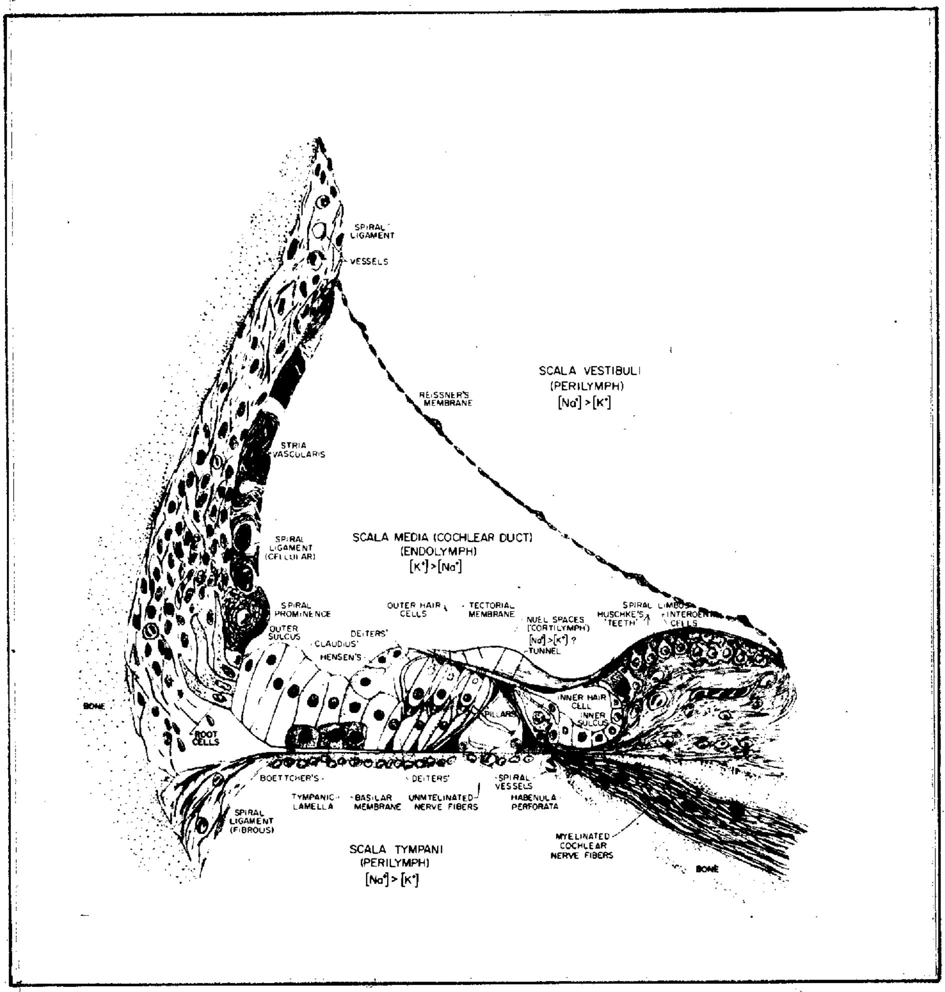

Figure II.4. The organ of Corti. From Hawkins (1966 a) peripheral side, (together with supporting cells of Deiter and Hensen). These cells are the sensory receptors, ultimately responsible for the peripheral coding of the auditory signal.

II.2.3 Basic Neuro-Anatomy of Hearing and the Auditory Pathway

Although the neuroanatomy of hearing has been under investigation for more than a hundred years (e.g. A. Corti, 1851) an accurate and detailed description of the peripheral innervation has been available only for the last decade or so. Recent (1967) electron microscope observations performed by a number of workers on the innervation of the organ of Corti (Spoendlin,(1968); Engstrom,(1966)) have revealed a complex, (and in some case unexpected) pattern of distribution of the nerve fibres to the sensory receptors. Their findings cannot be left aside in the present study in particular since, as emphasised by previous workers, an important objective in psycho-acoustic experiments is to relate the psychophysical behaviour to detailed peripheral mechanisms. (Bekesy,(1960); Flanagan,(1963); Lynn and Sayers,(1970); Sayers,(1966); Toole,(1965))

Neuroanatomically, the starting point of the auditory pathway is the Organ of Corti; at this point the sensory receptors are connected to higher auditory centers via the auditory nerve, also referred to as the cochlear division of the eighth cranial nerve.

The auditory nerve contains some 30000 myelinated afferent fibres, (Rasmussen,(1941) quoted by Whitfield,(1967)), together with 500 of the efferent types forming the olivo-cochlear bundle. The afferent fibres originate from bipolar cells whose body is situated in the internal ear, inside the modiolus. The cells' bodies are distributed along the osseous spiral lamina to form the spiral (or cochlear) ganglion. The efferent, unmyelinated, fibres however originate in 80% of the cases, from the contra-lateral cochlear nucleus, (crossed efferent fibres), the remaining from the homolateral cochlear nucleus. (uncrossed efferent fibres)

From the spiral ganglion, the afferent fibres reach the sensory receptors through narrow opening in the spiral lamina, (habenula perforata) where they lose their myelin sheath. (figure II.5) From this point they are directed either to the inner hair cells or the outer hair cells, and in each case they travel either radially, (i.e. transversely to the basilar membrane) or spirally (along the basilar membrane), hence giving rise to four types of fibres: inner and outer radial fibres, inner and outer spiral fibres.

Although the pattern of cochlear innervation appears to be fairly complex, the situation is somewhat simplified at least as far as the arrangement of fibres is concerned in the auditory nerve: in fact the majority of afferent fibres are of the inner radial type and terminate on few (perhaps one) inner hair cells. In this case, the auditory nerve can be thought of mainly as the medium by which the neural information emanating from a precise region of the basilar membrane is carried to higher auditory centers.

From the spiral ganglion, in the cochlea, the auditory nerve is directed to the cochlear nucleus, (figure II.6) where an intricate innervation scheme is encountered, i.e. each fibre connects with several hundred cells in the nucleus. A group of fibres leaving the cochlear nucleus is then directed to the superior olivary complex where afferent connection, important to binaural fusion, are made with fibres from the contra-lateral nucleus.

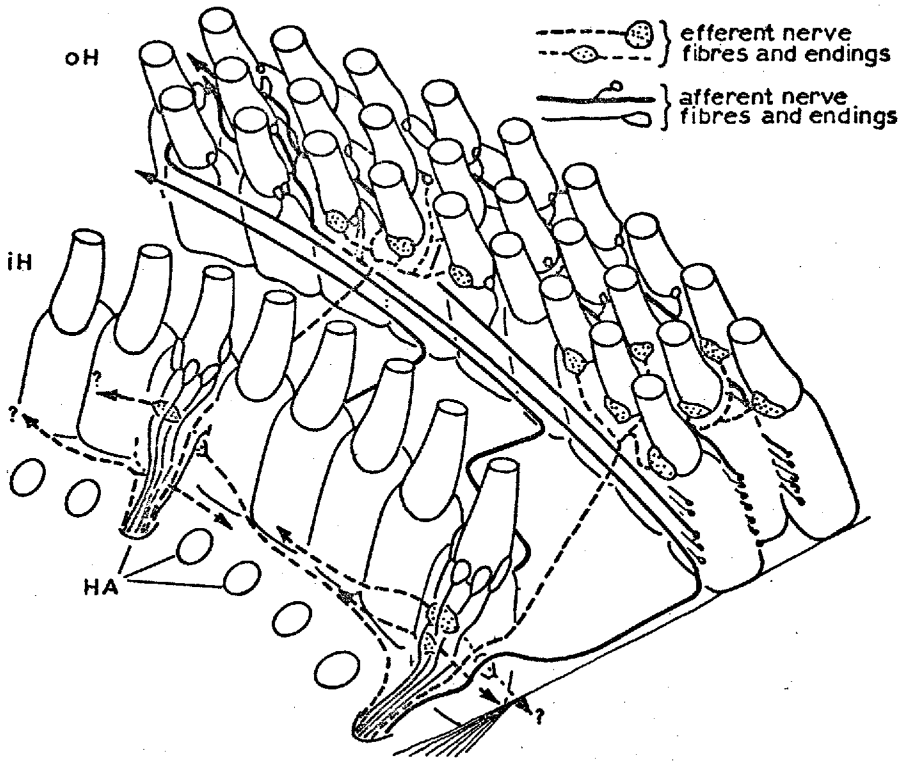

Fig. II 5. Schematic drawing of the innervation of the organ of corti in cat. Afferent fibres are represented by solid lines, efferent fibres by dashed lines. Those terminating on outer hair cells are shown as thick lines. Outer hair cells (oH), inner hair cells (iH), and openings of the habenula perforata (HA). The nerve fibres and endings indicated do not correspond to their actual numbers.

From Spoendlin, (1967).

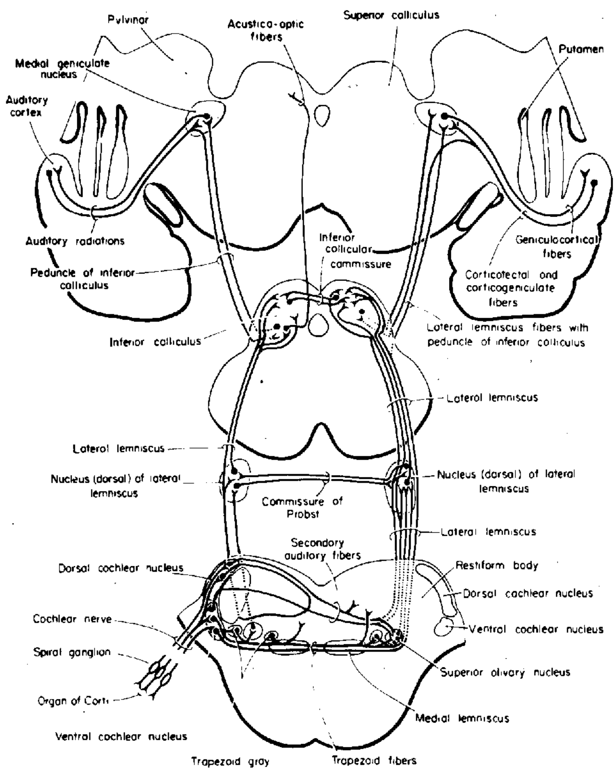

Figure II.6. The auditory pathway. From Hawkins, (1966 A).

From the olivary complex, itself constituted of five nuclei, the binaural signal passes through complex "relay station" (inferior colliculus, medial geniculate body) to finally terminate at the auditory cortex.

The important point that this description emphasises is that right from the cochlear nucleus onward, the pattern of innervation is immensely complicated; although tonotopic organisation can be found at nearly all levels of the auditory pathway, the functional relationship between the neural activity generated at various nuclei and the peripheral acoustic signal is far from being simple.

Because of this situation, the most attractive physiological recordings of single auditory fibre activity are the one taken from first order auditory neurones (pre-cochlear nucleus); as pointed earlier, the majority of these fibres connect to precise cochlear regions of the basilar membrane, a most helpful anatomical fact in the understanding of the peripheral coding of acoustic signals. This question will now be dealt in more detail.

II.3 Peripheral Coding of Acoustic Transients

II.3.1 Basilar Membrane Mechanical Response

A knowledge of the mechanical properties of the inner ear is of a prime importance to the understanding of the neural coding of auditory signals; this topic will be briefly introduced here.

In response to rarefaction transients, the tympanic membrane is pulled outward, thus producing via the ossicular chain a similar, but smaller, displacement at the oval window. In turn, this sets up a pressure difference between the scala vestibuli and scala tympani, that results in the basilar membrane being pulled upward. Because the mechanical properties of the membrane, (width, stiffness, etc.) gradually change from cochlear base to apex, successive points on the membrane will not wholy move in phase with respect to each other, and a travelling wave will result.

Measurements taken by Bekesy,(1960) and more recently by Rhodes,(1971), provided quantitative descriptions of the frequency response (amplitude and phase) of the basilar membrane displacement; indirectly, these lead to the membrane response to acoustic transients (impulse response), on the assumption that this system is linear.

Bekesy's measurements (figure II.7), have shown that the membrane, at any particular point, behaves like a mechanical band-pass filter, whose center frequency (place frequency) varies according to the position on the cochlear partition: at the basal end, the membrane was found to be maximally sensitive to high frequency signals, while low frequency sensitivity appeared at the apical end.

From Bekesy's measurements the impulse response of the basilar membrane has been computed by Flanagan,(1965): it has been

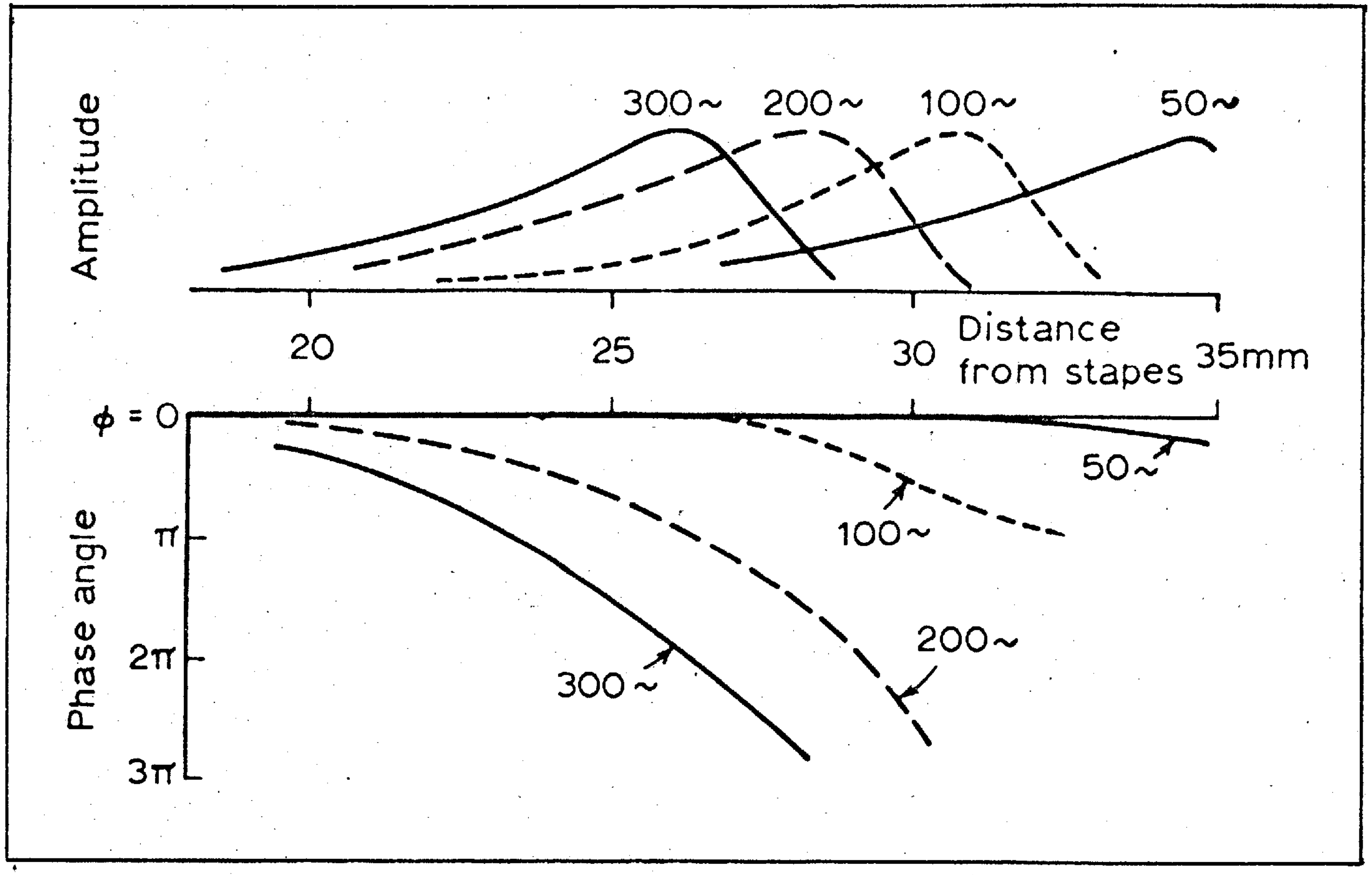

Figure II.7. Basilar membrane mechanical response. From Bekesy, (1947), quoted by Whitfield, (1967).

shown that, in response to an acoustic transient, a basilar membrane locus displays several (3 or 4) damped oscillations at the frequency to which the place concerned was found to be most sensitive. The very recent measurements reported by Rhodes,(1971) suggest however a slightly less damped system, and perhaps there are a few more oscillations in response to a transient.

II.3.2 Mechanical to Neural Transduction

The discharge pattern of first order auditory neurones has been reported in detail by Kiang and his co-worker,(1965). In figure II.8, neural responses to rarefaction and condensation clicks are shown for various levels of stimulus intensity: the neural activity is presented in the form of a Post-Stimulus Time (P.S.T.) histogram.

This particular example shows that the temporal coding of neural activity closely relates to the mechanical events in the cochlea: successive peaks of the P.S.T. histograms appear separated by a period that corresponds to the inverse of the characteristic frequency of the fibre concerned. (i.e. the frequency at which the fibre is most sensitive): a fact consistent with the view that the particular fibre innervates the region of the basilar membrane maximally responsive to that frequency.

Figure II.8 also shows that the receptors display an apparent unidirectional sensitivity to basilar membrane displacement: very little neural activity is seen between the peaks of the histograms; this is also suggested by the fact that the modes of the rarefaction P.S.T. histogram interleave the modes of the condensation histograms. In particular it appears that the neuron is responsive

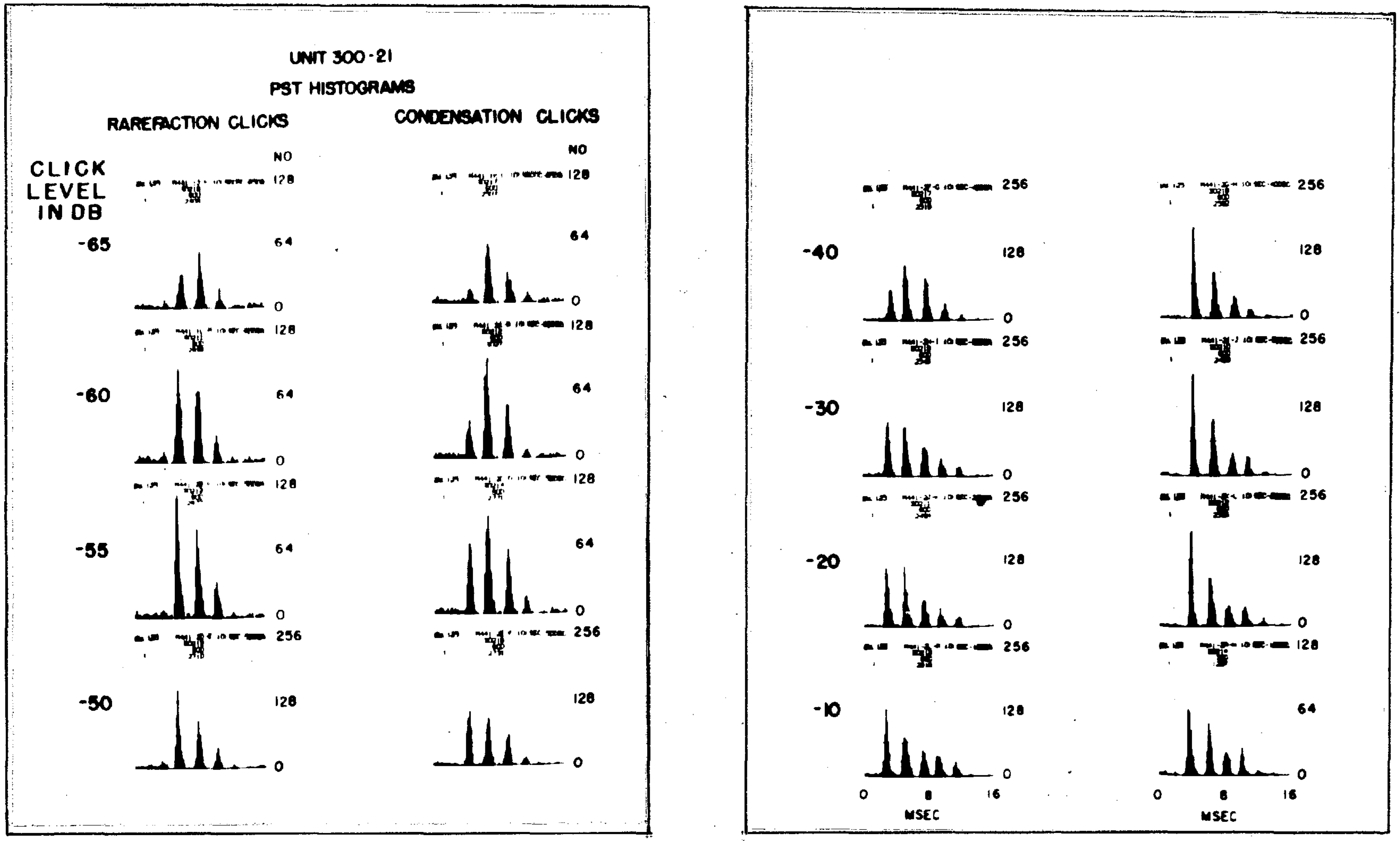

Figure II.8. P.S.T. histograms of neural activity recorded from a single afferent fibre of the auditory nerve at various stimulus level. From Kiang, (1965).

only during the rarefaction phases (upward movement of the basilar membrane): the earliest peak to be observed at high intensity is indeed seen in the rarefaction clicks histograms.

The unidirectional sensitivity is not however the only form of non-linearity that can be observed in these results. This particular point is illustrated by the changes in relative amplitude of various peaks of the P.S.T. histograms, as the stimulus level is increased: as intensity is raised, a new peak becomes apparent, grows and finally dominates. This phenomenon (the gradual suppression of later peaks in the histograms) has been interpreted by Lynn,(1970) as resulting from refractory properties of the auditory neurone: raising the probability of firing during the first rarefaction phase, (as presumably does an increase in stimulus intensity) thus reduces the firing probability during later rarefaction movements.

The picture of the peripheral coding presented here is undoubtedly an oversimplified one: for instance it does not show the effects of afferent (two tones) and efferent inhibition. As we shall see, it nevertheless contains the features essential for a basic understanding of the binaural interaction mechanism dealing with auditory transients.

II.4 A Recent Model of Binaural Interaction

The particular attribute of hearing with which this study is concerned is referred to as binaural interaction, a phenomenon essentially underlying sound localisation and spatial auditory discrimination. Based on measurements aimed at quantifying various aspects of this faculty, models have been proposed that replicate the observed psycho-physical behaviour. (Sayers and Cherry,(1957); Bekesy,(1960); van Bergeijk,(1962).

Of a particular interest to the present study is a model recently formulated by Monro,(1971) that uses the neural coding of the acoustic signal (rather than the acoustic signal itself), as the object of binaural interaction; it was presented as a "revised cross-correlation scheme", essentially including in an operational model (formulated earlier by Sayers and Cherry) the more recent physiological data related to the auditory periphery, (mechanical events in the cochlea and associated neural coding).

II.4.1 Sayers and Cherry's Cross-Correlation Model

The model of binaural interaction presented by Sayers and Cherry,(1957) is illustrated in figure II.9; it is meant to describe from an operational point of view, a possible mechanism that could account for localisation and discrimination of complex sounds. Being non-specific about the physiological minutiae, the authors propose that, monaurally, the acoustic signal is first subjected to a running auto-correlation operation thus providing an additional dimension (auto-correlation delay), prior to the

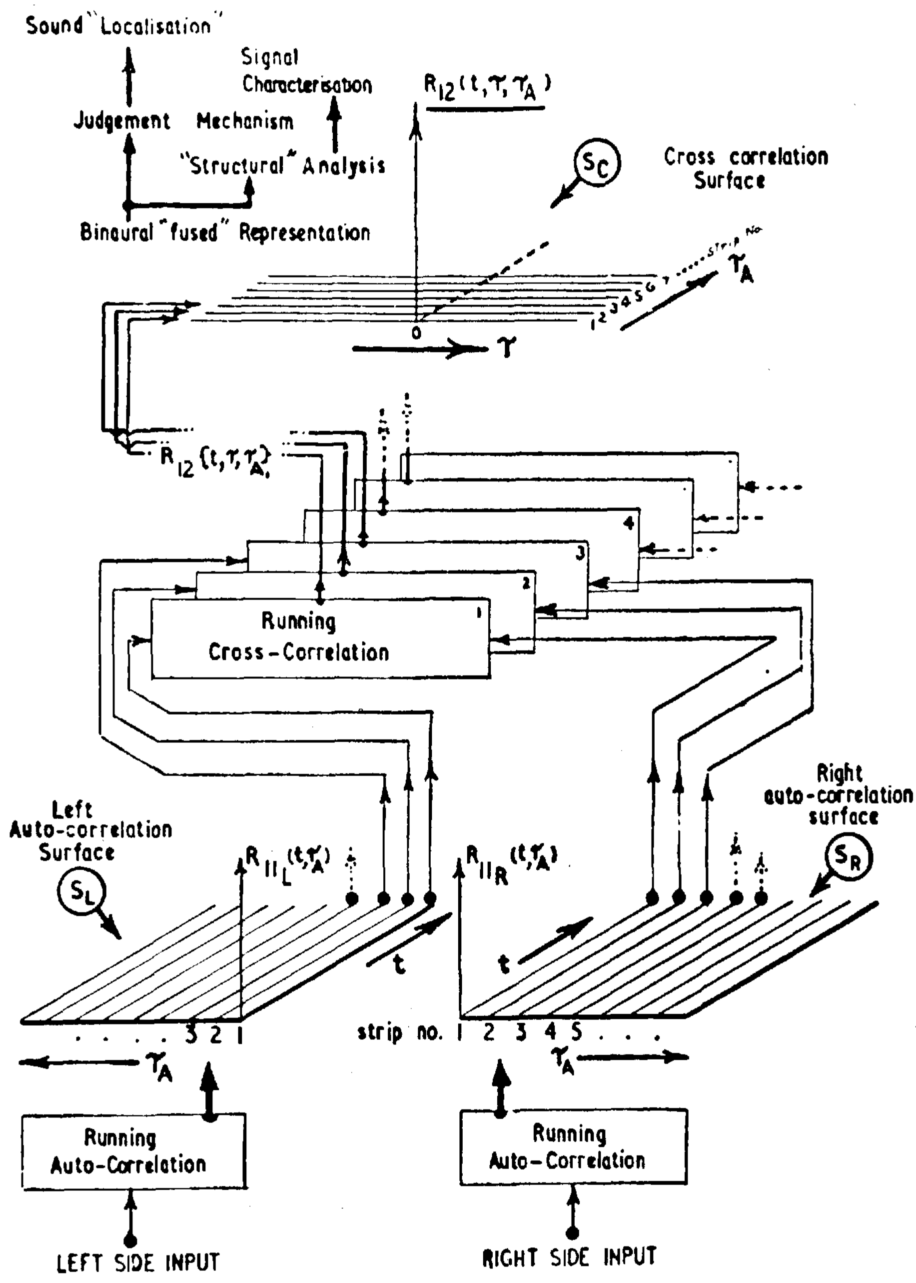

Figure II.9. Model of binaural interaction.
From Sayers and Cherry, (1957).

binaural interaction: this is presented as an extension to a model previously formulated in order to explain the ability of listeners to lateralise a complex two tone chord as a single image or as an image of either of the two constituents as if they occurred alone.

Then, for each auto-correlation delay, the signals from both ears are cross-correlated (running cross-correlation): this procedure enables the mechanism to extract the inter-aural time information from the binaural signals, regardless of the nature of the signals, (noise, speech, etc.). The binaural interaction, per se is then represented on a cross-correlation surface that provides, to higher functions, the necessary elements for a decision process capable of identifying position of acoustic images, and of discriminating in favour of one source against another: this is done by selecting the appropriate point on the correlation surface.

II.4.2 Monro's Model of Binaural Interaction

The model presented by Monro,(1971) in essence is identical, and differs only in the form in which some of the functions are achieved. Taking into account the important peripheral transformations (mechanical and neural events) imposed on the acoustic signals, firing probabilities of first order auditory neurones are computed at some 46 representative cochlear loci (covering the range of place frequency from 300 hz to 3000 hz.).

This is done by, first computing the mechanical response of the basilar membrane to an acoustic stimulus, using Flanagan's (1965) approximation formula; Gray's detailed analysis (1966) on probability of firing (of a first order auditory neurone) then provides an analytical expression to enable the "transduction" from membrane displacement to recovered firing probabilities (i.e. firing without refractoriness). Refractory properties are subsequently introduced to replicate the changes in relative amplitude of the peak of the P.S.T. histogram (figure II.8) as the stimulus level is increased.

The binaural interaction consists, in this model, in cross-correlating the firing probability functions emenating from corresponding place frequencies of the cochlea; arrayed side by side the cross-correlation functions produce a conceptual surface representing the perceptual field: in this way binaural images arise as maximum value of interaction (cross-correlation) at a particular membrane place and delay.

To illustrate the strength of binaural interaction, (cross-correlation magnitude) for various cochlear places and correlation delays a contour plot is utilised. Figure II.10 is an example of binaural interaction simulated in this model; the stimuli are single clicks presented with an inter-aural amplitude difference (I.A.D.) of 10 decibels.

III.4.3 The Multiple Binaural Images

The important point evidenced by this representation is the existence of multiple images associated with the binaural interaction of even simple auditory transients. In this particular example, a first dominant image arises along the whole basilar membrane shifted from zero inter-aural time delay (I.T.D.) by some 100 µsec.

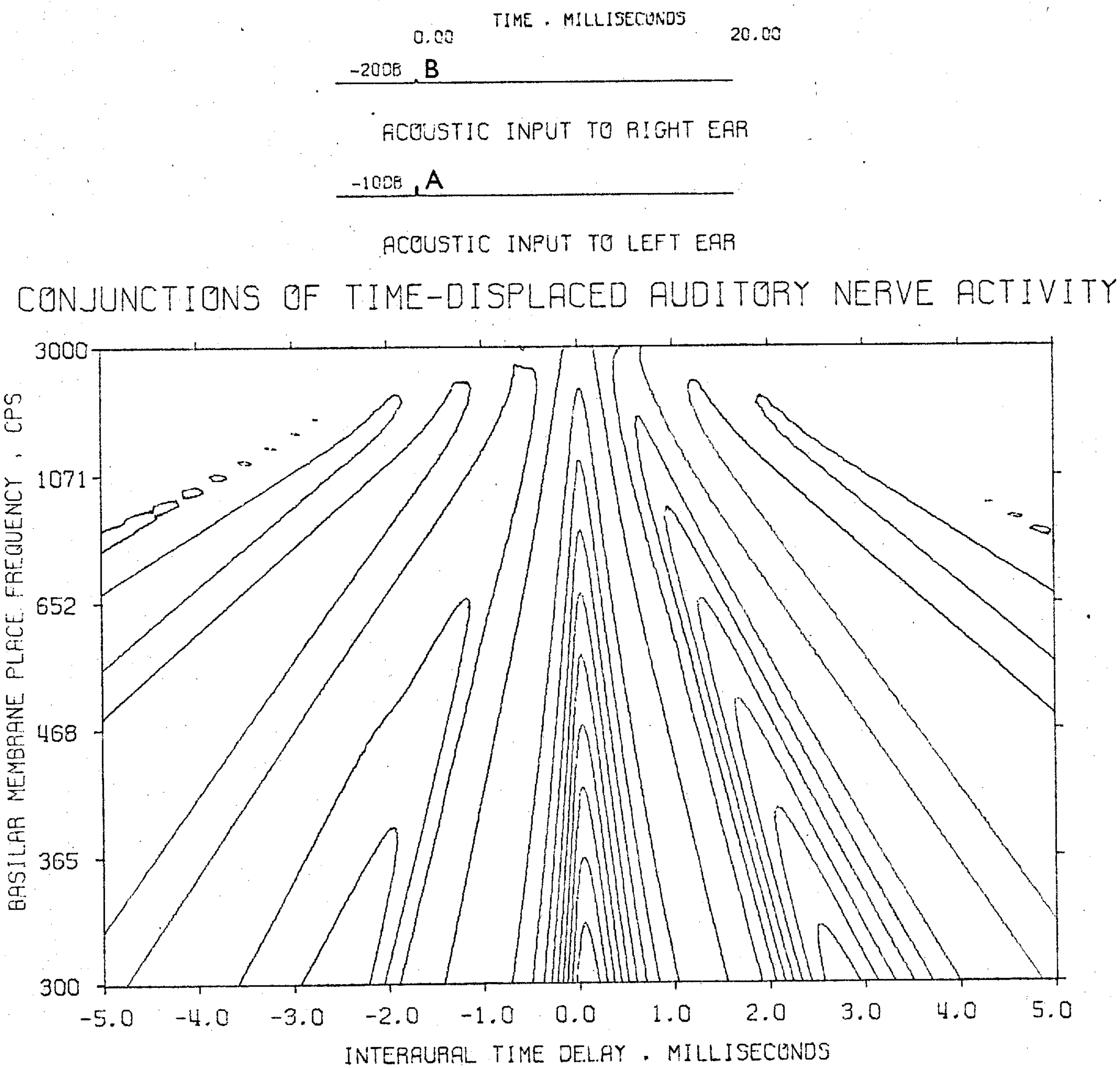

Figure II.10. Simulated binaural images. From Monro, (1971).

This time shift results from the introduction of an I.A.D. that produces differences in the latency of the first peak of neural activity emanating from corresponding cochlear places: accordingly a time-intensity trading ratio of 10 µsec/db can be associated with this particular image.

A significant secondary image is also represented in this simulation: resulting from the interaction of the second rarefaction motion in one ear with the first rarefaction in the other, the image appears at an I.T.D. that varies according to the selected place frequency. The lack of place frequency sensitivity of the model does not enable one to see which particular basilar membrane locus is most likely to be chosen by the listener and, consequently, at which I.T.D. the secondary image arises. Monro himself is not specific on this point; however other workers (Sayers,(1966)) have suggested that in binaural interaction of auditory transients, the 1 kz region of the basilar membrane was dominant, a fact that enables one to position the secondary image with an I.T.D. of 1 msec.

It may prove to be important that in a binaural experiment with I.A.D. it could happen that the listeners attention is spontaneously directed to this secondary image, rather than to the "dominant" one mentioned earlier; this shift of attention may then (erroneously) be interpreted as resulting from a trading between time and intensity, in the sense that we presented it before; in such circumstances, the psycho-physical measurements of the trading ratio would lead to very high values (100 µsec/db in the case of the simulation presented in figure II.10). This question has been discussed by Monro,(1971) and we will report some experiments that relate to this matter.

II.4.4 Concluding Remarks

The interest of the binaural interaction model formulated by Monro lies in the representation of a perceptual space that closely relates to the important peripheral transformations (mechanical and neural) imposed on the acoustic signal. Because of the way the various probability functions are generated, the model is directly applicable to a general class of complex stimuli, resulting from the combination of simple transients. The numerous peripheral non-linearities make difficult a visualisation of the associated neural coding at various place frequencies. Hence the subsequent interpretation of the related binaural interaction is, without a proper representation of the binaural space, a most difficult task. In such circumstances, we found the model's visual description a most useful assistance.

It will prove to be possible to use the model also to describe the formation of the multiple images, the investigation of which will be reported later. This point will be a major concern in the present study which examines conditions in which attention is paid to one particular image in preference to another.

CHAPTER III

EXPERIMENTAL TECHNIQUES

III.1 Introduction

The present chapter describes the experimental techniques used throughout the course of this study, together with the associated apparatus, while other experimental methods are also reviewed. A more technical description of the various instruments specifically designed for the purpose of the present research will be detailed in appendix A. Short form specifications will be reported here together with some preliminary tests; these comprise performance tests and the analysis of the specific acoustic signals used in our experimental set up. We have also included six Bekesy audiometric tests performed on the subjects who participated in the various experiments.

Figure III.1 shows the wiring diagram of a simplified binaural experiment.

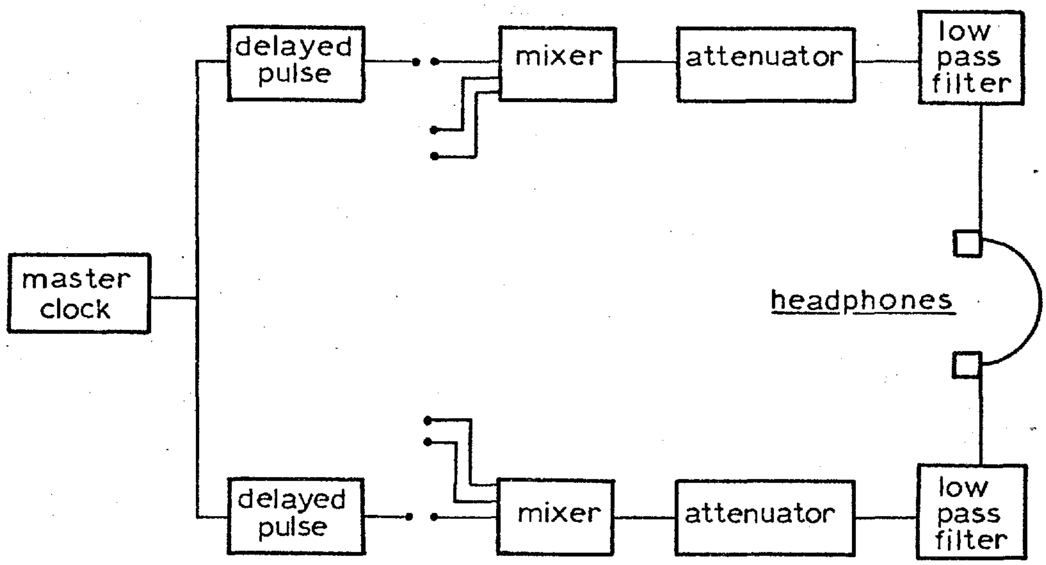

Figure III.1 Simplified binaural experiment

Such a simple set-up, perhaps because of its simplicity, has been widely used by a great number of psycho-acoustic workers in order to investigate various aspects of auditory perception. For the experimenter, it has the advantage of being very versatile in terms of variation of the binaural input signals, while the transient nature of the generated waveform optimizes the conditions for the study of binaural fusion.

There are two important classes of binaural experiments that can be generated in this way. In the first case, the subject is asked to report the position of the lateral displacement of the acoustic image resulting from the fusion of the right and left ear signal. If experiments of this type are repeated for various values of one of the many possible parameters (time delay, attenuation, cut off frequency of the filters, etc.), trajectories of sound image can be found as a measure of a behavioural response. A particular application of this technique is sometimes referred to "judgement of sideness experiment" (Bekesy,(1960)) generating binaural coherence curves (Sayers, (1957); Cherry, (1956)). An interesting example of its usefulness is reported here.

In an experiment performed by Cherry and Sayers, the subjects were asked to report the sideness of the image resulting of the fusion of two phase different, but otherwise identical, sinusoids. The value " 1 " was assigned to a left judged position, " 0 " to a right judged one. For a given phase difference presentation, approximately 20 values of sideness were averaged. Figure III.2 illustrates the effect of varying the phase of the acoustic sinusoid on the averaged sideness judgement, at a particular frequency. It shows that the subjects behaved like a system having a very high gain with saturation characteristics, degenerating progressively as the frequency is increased. This establishes in a quantitative manner that, as far as phase difference is concerned, lateralization judgement of sinusoidal signals can only be achieved at frequency below 1.5 to 2 khz; therefore at higher frequency some other mechanism,

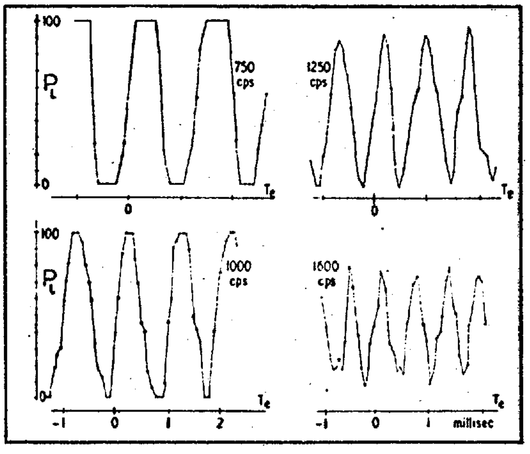

Figure III.2 Binaural coherence curves for a single sinusoid. From Sayers and Cherry, (1956). P_L is percent judgement to the left; T_e is interaural time delay, positive defining left leading.

such as interaural amplitude difference for instance, must be responsible for localisation of sound in natural circumstances, in so far as this is possible. This view is supported by the fact that, for frequency above 1.5 khz, i.e. having a wavelength shorter than 20 cm, the width of the head would not permit a single valued relationship between horizontal position of a source of sound, and the perceived phase difference at the site of each ear.

The psycho-correlogram, or binaural coherence curve does not however use the full potentiality of the human observer, who in general, is capable of making graded positional judgement, or, to put it in digital terms, of having a resolution better than one bit. Therefore later psycho-acoustic experiments were performed, recording judgements of image position, rather than sideness. In this instance the subjects were required to assign and report a position to each binaurally fused sound image, with the aid, but not necessarily, of a visual scale. Advantageously, this method, as illustrated by figure III.3, necessitates a smaller number of judgements, to obtain a reasonably smooth average out of the data.

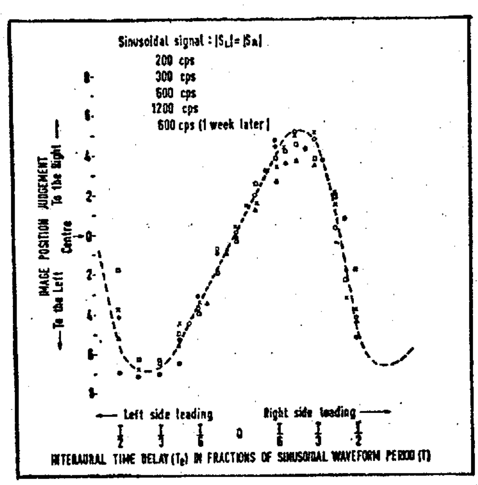

Figure III.3 <u>Judgements of image position against interaural time delay for a pure tone binaural signal, about 30 db SL.</u>

From Sayers, (1964, A)

Additionally, this particular technique offers the possibility of studying the over-all acoustic field, as opposed to the previous method that only enables one to study the central region of the field. Consequently, it gives a means of investigating the cases of multiple images coexisting and spread over the perceptual field, and thus has been successfully applied to explore the binaural interaction of pulses and pulse pairs. (Sayers, (1964, A), (1964, B); Toole, (1965))

The second class of binaural experiment that the arrangement of Figure III.1 can provide, is refered to as a binaural centring experiment. In this particular case, the subject is asked to alter the value of one of the experimental parameters (phase, amplitude,...) until he perceives the fused image to be centrally positioned in his subjective acoustic space. An investigation on the effect of interaural amplitude difference on binaural interaction of transients, performed by David et al., (1959) is an example of application of this technique. The subjects were presented with clicks having some interaural time difference, and were then asked to adjust the relative intensity until the sound image appeared to be centrally positioned; a time/intensity trading ratio could then be found at various intensity levels (figure III.4)

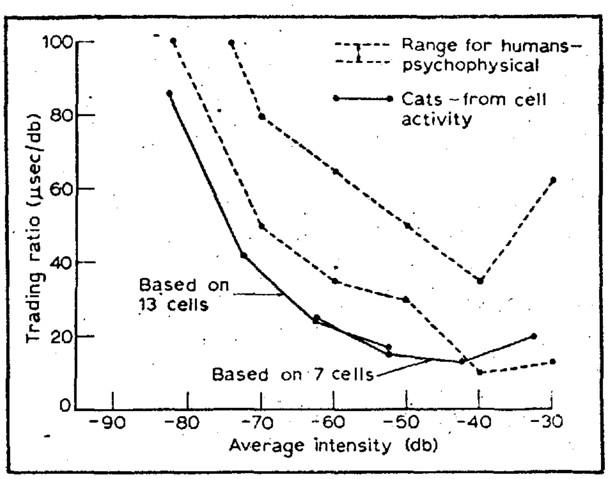

Figure III.4 <u>Range of time-intensity trading ratios obtained in centring experiment compared with the ratio for accessory olive cells computed on the basis of Hall's model.</u> Hall,(1964), from Whitfield,(1967).

The present investigation on dynamic aspects of auditory perception has been based on experiments of this type, i.e. binaural centring. Rather than the amplitude difference, the parameter the subjects were required to adjust was the inter-aural time difference and consequently this was also the variable that was measured to evaluate the psycho-physical performance of the subjects. Compared to lateralization experiments, carefully designed centring experiments lead to results having a higher degree of reproducibility from subject to subject and, with a given subject, an even greater degree of consistency: we shall report in a later section results of centring experiments that support this view. At this stage however, a close examination of how a binaural centring judgement is performed will show various factors contributing to the comparatively high accuracy and reproducibility that has been mentioned.

Figure III.5 shows the time evolution of a typical binaural centring judgement. To our knowledge such results have not been reported elsewhere and therefore need further explanations.

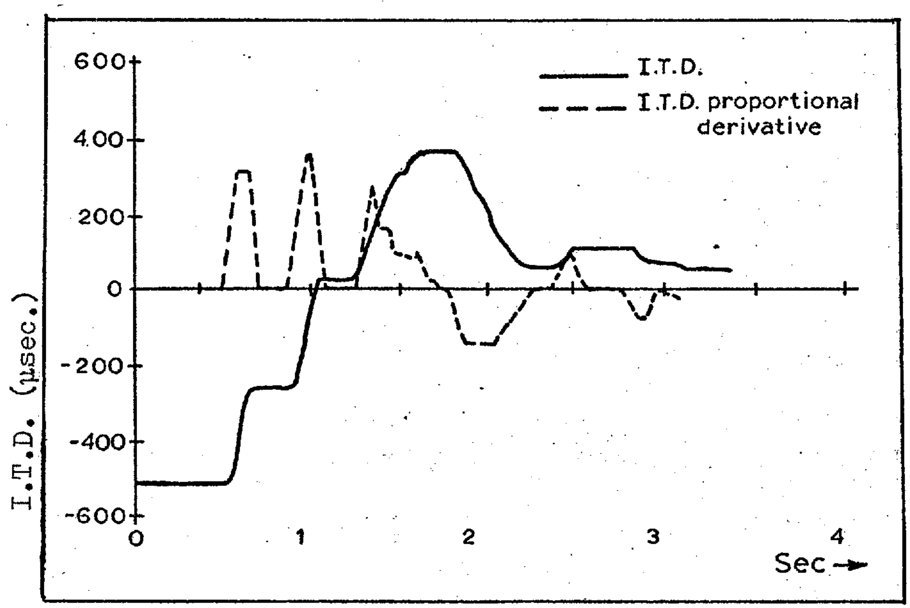

Figure III.5 Evolution of a binaural centring judgement showing how a subject adjusts the inter-aural time difference to re-centre an acoustic image. Input: Single clicks, 50 db S.L., 20/sec., low pass filtered at 2 kc. Left leading is positive delay.

In this experiment two trains of low pass filtered transients were presented binaurally with an initial time difference of 500 µsec.; the subject was asked to adjust the time relationship until he would perceive a centrally positioned image. The interaural time difference was sampled at the occurence of every pulse, i.e. 20 times per second. Therefore figure III.5 shows the interaural time delay as the subject modifies it in the course of performing a centring judgement. Clearly, this is illustrative of a process in which the subject, after having decided on the sideness of the image, scans his acoustic field and continuously judges the position of the image. An examination of the derivative of the centring function, computed as a finite difference betwwen successive samples, establishes alternate period of observation (plateau) and action (triangular waveform). This implies that several behavioural decisions are involved in the final binaural judgement.

Lateralization experiments must involve a totally different decision process: a subject reporting the position of an image does not have any means of immediately testing the accuracy of his decision and can only refer to his previous experience, which may need to go back as far as his last five or ten judgements. In a centring judgement process on the other hand, he dynamically tests his performace having reference to a recent past; consequently better performances are to be expected.

A comparison with other perceptual mechanisms reveals that sensory receptors are usually more sensitive when responding to changing input than they are to stationary ones; a mechanism of this sort may very well contribute to improve the accuracy and reproducibility associated with binaural centring experiments. Experimental evidence given by Levine,(1972), indicates that this factor may also be important in lateralization experiments since position judgements reported shortly after an image presentation were found to be more accurate than others.

III.2 Apparatus

This section describes the design of electronic instruments used in binaural experiments. The underlying design philosophy aimed at simplifying and improving the reliability of the normal experimental procedure. Accordingly, special attention was given to the specific instrumental functions considered to be critical to the issue of the present work.

III.2.1 Binaural Pulse Generator

A five channel pulse generator was designed to facilitate the realisation of binaural experiments. A photograph of the prototype is shown in figure III.6. Of a modular conception, the apparatus is made of a clock unit and five independent pulse generators of variable delay, pulse width and amplitude.

Each pulse generator module (P.G.M.) produces simultaneously three distinct and individually buffered pulse outputs. One output, of switcheable polarity and variable amplitude, is intended to be used as the audio signal in the experiment. The two other pulse outputs, of complementary polarity and fixed amplitude, are designed as trigger sources to any other P.G.M.: being individually buffered the crosstalk between the trigger signal and the audio signal is minimized.

The various trigger outputs (10) and the five trigger inputs were grouped on a single 3" x 2" patch panel; every possible triggering interconnection between modules can therefore be made by joining proximal sockets with very short cables. Such a design

Figure III.6. Binaural pulse generator.

was found to greatly improve the reliability of the experimental set up.

At the design stage, precautions were taken to ensure that the various P.G.M. would produce very stable and jitter-free delayed pulses. Indeed the prototype was found, in that respect, to offer better characteristics than most of the commercially available units. Figure III.7 illustrates the related stability specifications.

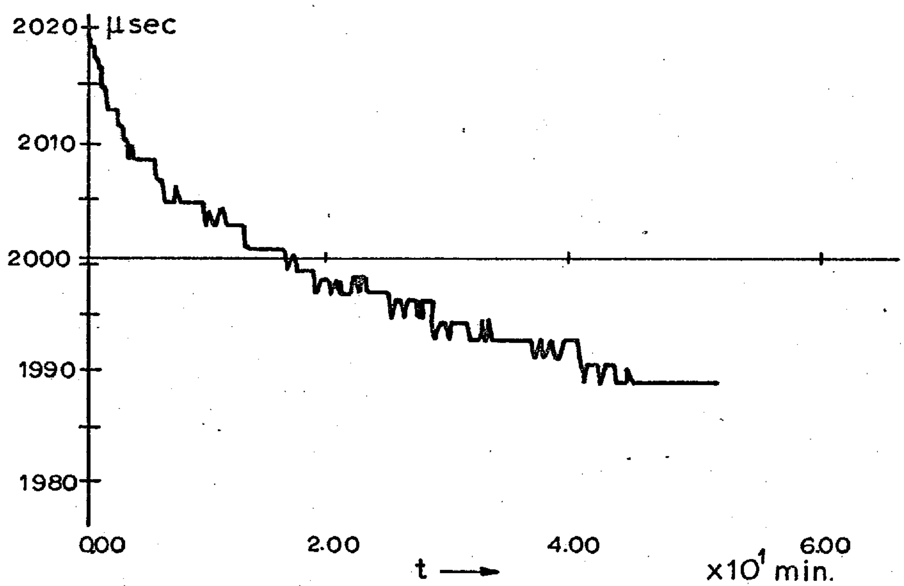

Figure III.7 <u>Drift characteristics of a delayed pulse.</u>
The unit was switched on at t=0. This also illustrates the magnitude of the jitter.

The unit was switched on at t=0, and with the aid of a time interval counter, the current value of the delay was recorded by a computer every 15 seconds for a period of one hour. This illustration indicates that a warming period of 20 minutes is sufficient to ensure that a particular setting of delay will not vary more than 0.5% per hour; a forty minutes warm up would be sufficient to reduce this rate to 0.1% per hour. As far as the jitter noise is concerned, it is seen to be $<$ than 1 μsec (0.05%); in this particular case it corresponds to the resolution of the recording apparatus.

A last remark on the binaural pulse generator concerns the programmable facility associated with the setting of a delay; three of the five units were modified to enable the use of an external voltage source to control the value of their respective delays.
A section of this chapter dealing with automated binaural experiment will show this to be an essential part of a computer monitored experimental procedure.

III.2.2 Audio Stereo Mixer and Buffer Amplifier

We mention here the design of a two channel mixer capable of algebraically adding five independent signals. The mixing function was obtained using integrated circuit operational amplifier, in a standard, unit gain, inverting adder configuration. The frequency compensation network that stabilizes the amplifier, was chosen with the aim of getting a high slew rate; in this way the rise time of high level pulses would not deteriorate through the mixing operation. The bandwidth of the prototype was found to be from dc. to 2 MHz.

A stereo, inverting, unity gain amplifier was also built using a similar technique. The buffering capacity was such that it could directly drive stereo headphones at comfortable level. A mute function consisting simply of a four pole relay was also incorporated in the instrument. In automated experiments, such a facility is essential to provide programmable resting periods of silence. Figure III.8 shows the prototype mixer and buffer amplifier built in a single instrument case.

Figure III.8. Audio stereo mixer and buffer amplifier.

III.2.3 Electrostatic Headphones

The listening experiments were carried out using Koss Esp.9 electrostatic headphones. These headphones, whose characteristic curves are in figure III.9, have exceptional wide-band frequency response, covering a range of 10 octaves: 15-15000 hz, ± 2 db. A very low harmonic distortion figure (0.2%) is made possible through the use of a push-pull action principle in the electrical to acoustical transduction process. The necessary bias voltage, required by most types of electrostatic headphones, is provided by an external voltage source: it ensures that the earphones will work properly even with very low level and low repetition rate signals.

Binaural fusion certainly involves processing of the phase characteristics of the signal perceived at the site of each ear. In headphones listening experiments designed to study some aspects of this fusion mechanism, it is consequently very important to ensure a good phase matching of the two headphones. Disregarding a constant level of sensitivity difference throughout the frequency range, visual inspection of figure III.9 indicates a very good amplitude matching, in the order of 0.5 decibels; this would suggest that the two phase characteristic curves would look very much alike. Unfortunately, technical information on that matter is not provided, nor specified by the manufacturer. We will report in the next section details related to this point.

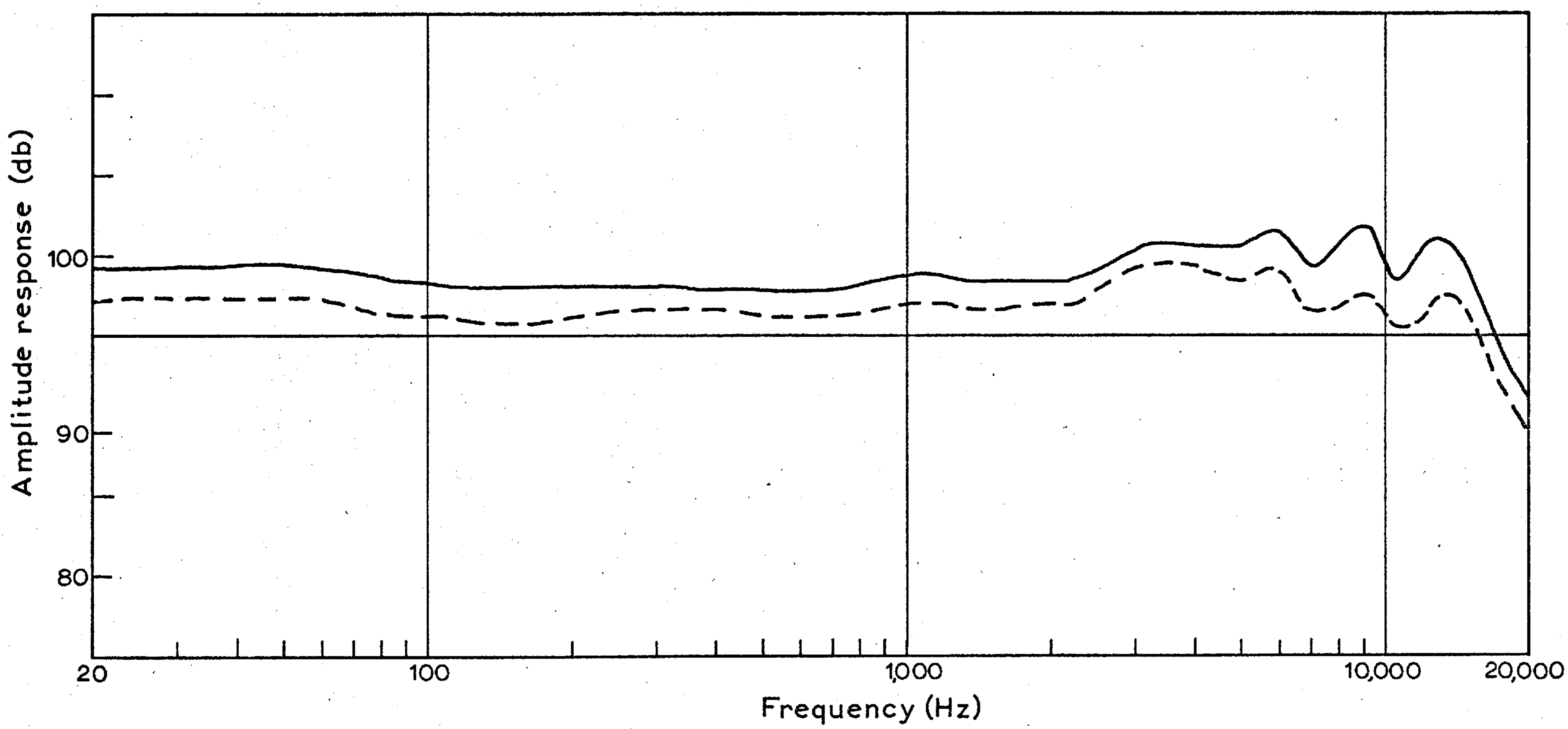

Fig. III.9 Response curve of Koss Esp-9 headphones. Solid line represents response of the left headphone while the dashed line represents response of the right one. The zero db reference corresponds to a pressure level of ·0.002 dynes/cm^2. 3 volts input.

III.3 Acoustic Nature of the Signal Generated from the Binaural Experiment System

The apparatus utilized to produce the binaural signals used in our experiment was tested so as to evaluate the acoustic properties of the output transient generated from the entire system. An investigation of this sort was neccessitated by the fact that some pieces of information were missing: no input-output relationship could be worked out, since the phase characterisitic of the headphones had not been previously established. Furthermore, in order to make sure that the acoustic signals were meeting our requirements in vivo, it was found desirable to look at the output of the complete system rather than deduce its nature by the characteristic of each component. Accordingly, it was decided to study only the specific case where the experimental situation was duplicated, i.e. a low-pass filtered (0-2 khz) and a band-pass filtered (1-3 khz) acoustic transient. The testing procedure has been carried out as illustrated in figure III.10.

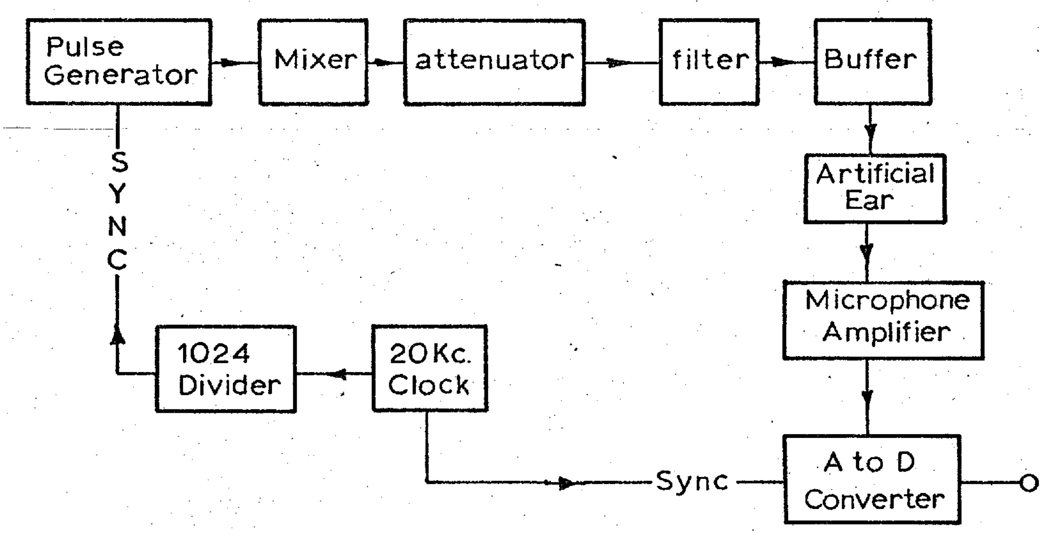

Figure III.10 Acoustic signal test schematic

The apparatus was set so as to reproduce the situation of a binaural experiment: one pulse generator was used feeding into a mixer a pulse of 100 µsec, with an amplitude of three volts. The mixer was itself connected to a 600 ohms attenuator[1] (set at zero db for the present situation) in series with a low-pass filter[2] with a cut-off frequency set at 2 khz. The output of this filter was then connected to a buffer amplifier used to energize the headphones[3].

The acoustic output was examined using an artificial ear[4] with a flat plate coupler for circumaural headphones. A microphone amplifier[5] set to have a bandwidth of 2-40000 htz. was used to bring the output level to about 1.4 volts.

This voltage pulse was then A. to D. converted using an IBM 1800 computer; the conversion was done at a rate of 20000 kc. and the digital result stored on tape. In order to reduce the noise components of the signal, picked up microphonically and electrically, an averaging technique was used. For that purpose a 1024 divider, consisting in a series of ten flip-flops synchronized by the same clock as the A. to D. converter was acting as a clock for the pulse generator. Following this, blocks of 1024 data values read from the magnetic tape where added, thus reducing any uncorrelated noise.

Approximately 100 impulses were averaged to give the results of figure III.11. Here the acoustic signal recorded for the right and left headphone is shown with the corresponding electrical impulse

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1) Solatron Laboratories, type AT 201

2) Alison Laboratories, type AL2B

3) KOSS ESP-9, electrostatic studio monitor

4) Bruel and Kjaer, type 4109

5) Bruel and Kjaer, type 2603

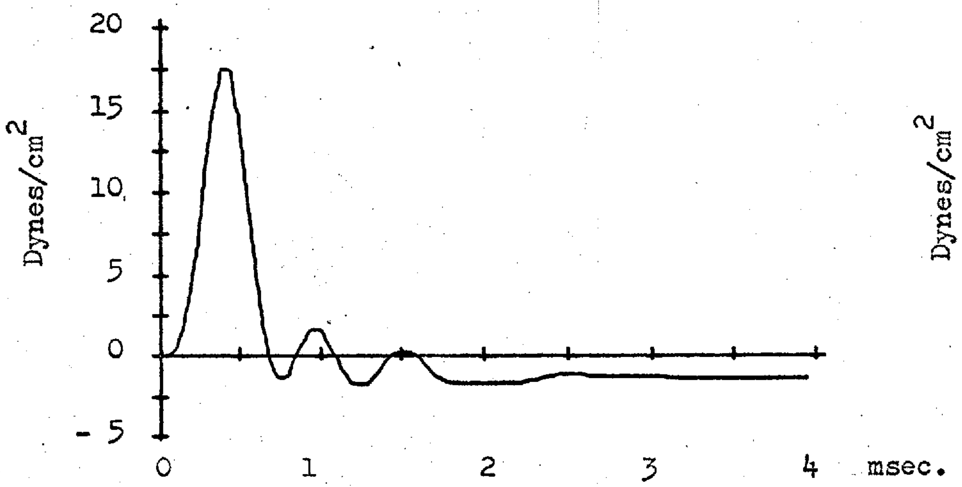

Figure III.11 a

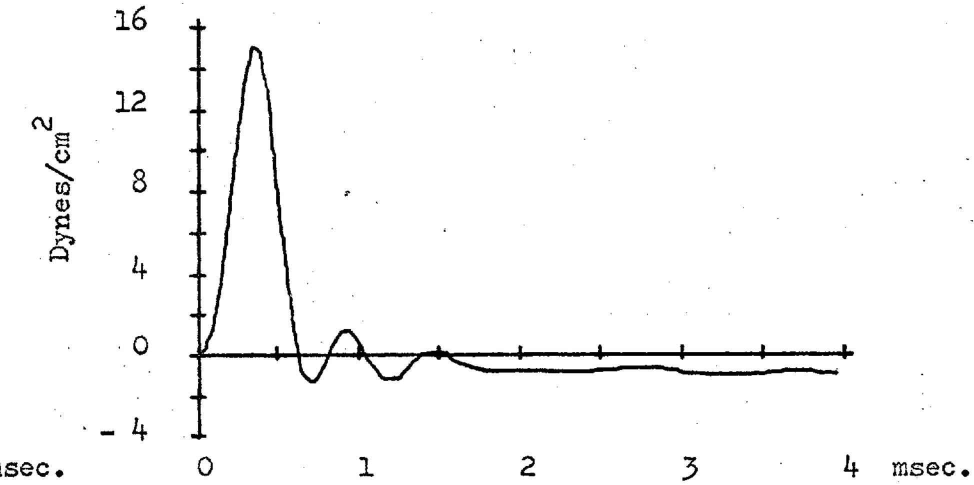

Figure III.11 b

Figure III.11 Pressure waveform of rarefaction clicks with Koss esp-9 earphones. The input is a 2 khz low-pass filtered impulse

Figure a:	Left earphone
Figure b:	Right earphone
Figure c:	Electrical input.

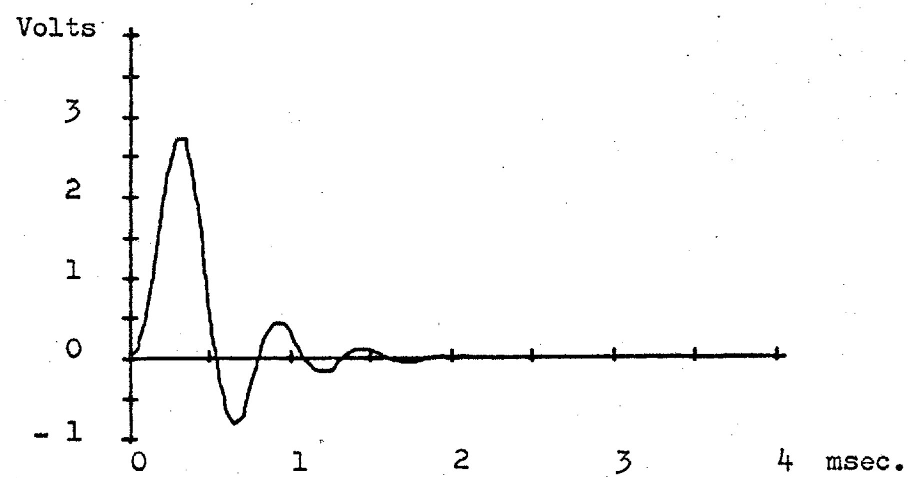

Figure III.11 c.

recorded from the input to the headphone. The agreement between electrical input and acoustical output is very good as was expected from consideration of the characteristic curves of the phones.

There are however some dissimilarities: the acoustical output shows a shift of the base line not present with the electrical input; this shift corresponds in fact to an exponential decay having a time constant of approximately 10 msec; such a time constant is associated with a cut-off frequency of about 15 cycles which is the low cut-off frequency of the headphone. A second difference can be seen by looking at the amplitude of the first undershoot, definitely bigger in the case of the electrical input; this difference is due to a first reflection on the microphone in the flat plate coupler-earphone cavity, and is illustrative of some of the problems that could be present in headphone experiments using higher pitched impulses.

Figure III.12 shows the individual Fourier transforms of those impulses. Except for values of frequency below 150 hz, where the effect of interference from the main could not be completely filtered in the averaging process, it can be seen that the amplitude characteristic curves match within 1 db, and the phase curves within 5°. The noise appearing on these plots at frequencies higher than 2.8 kc. is a consequence of the analog to digital conversion limited in resolution to 11 bits. The sharpness of the filter used in the present setting reduces to noise any part of the spectrum $1\frac{1}{2}$ octave higher than the cut-off frequency.

Figure III.13 illustrates the second type of acoustic transient used in our experiments: a pulse, bandpass filtered between 1 to 3 kc. Here again very good matching characteristics are shown for each headphones and similarly, good reproducibility

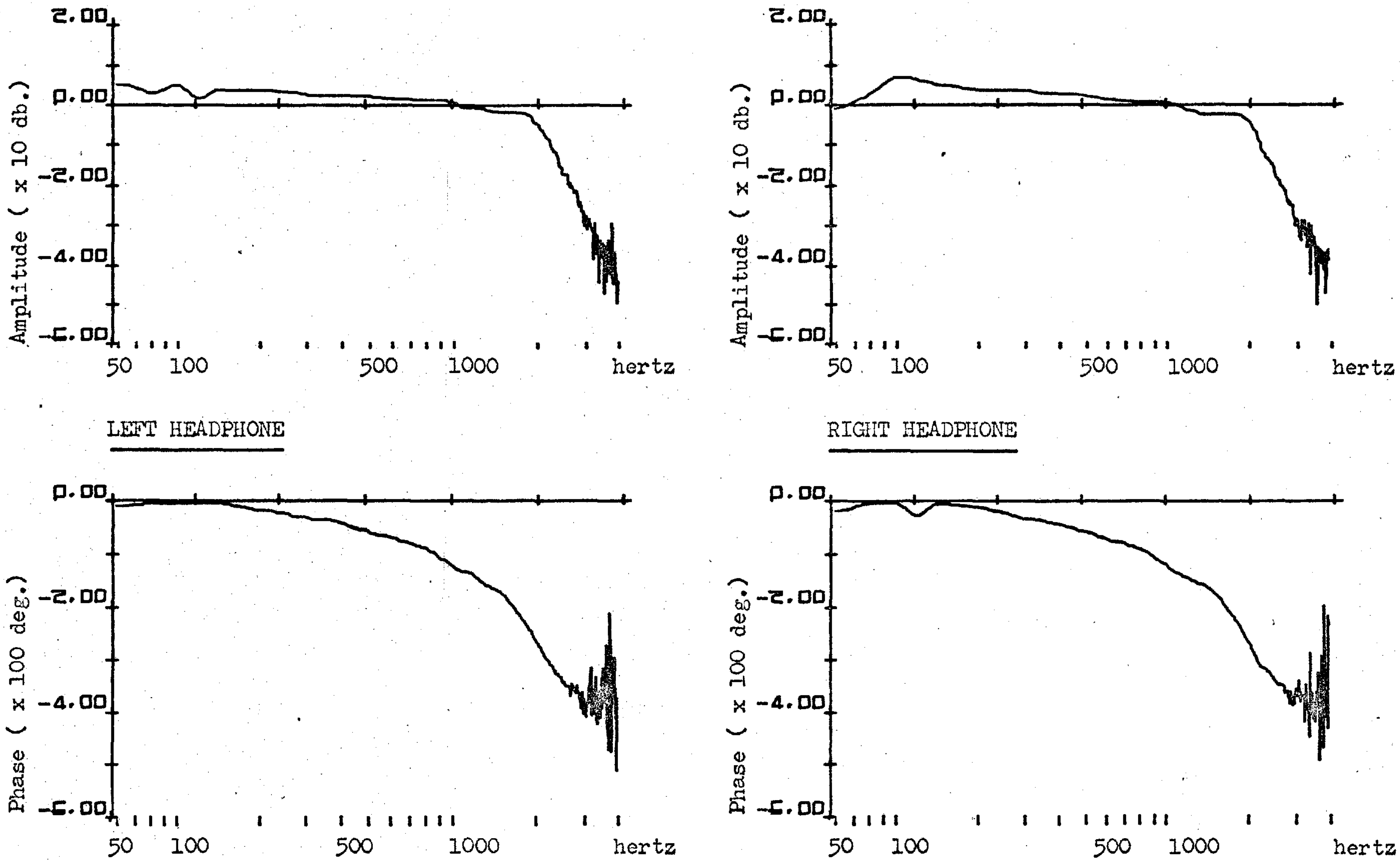

Figure III.12. Spectra of the acoustic transients. The input is a 2 khz low-pass filtered impulse

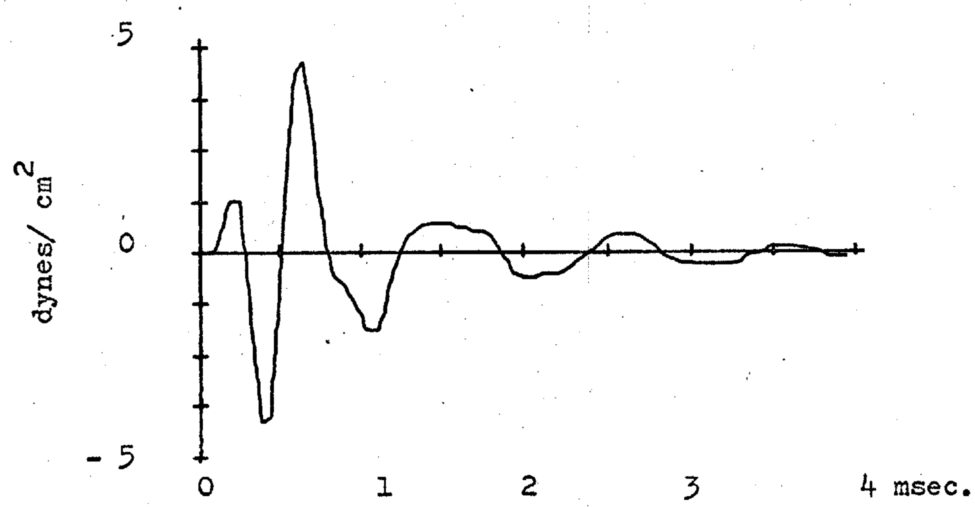

Figure III.13 a.

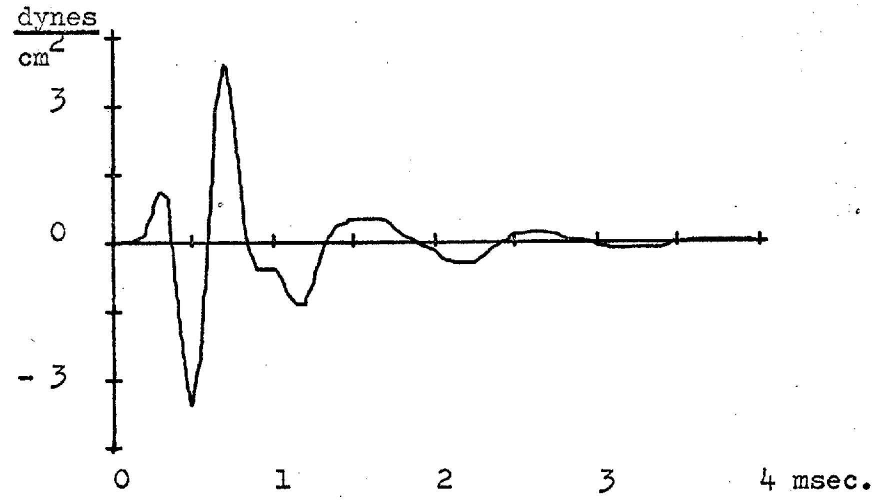

Figure III.13 b.

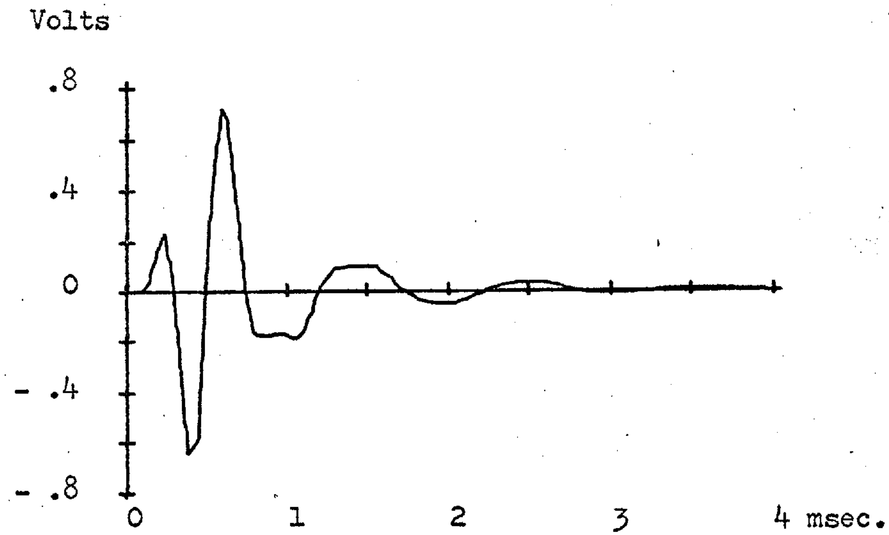

Figure III.13 c.

Figure III.13 Pressure waveform of rarefaction clicks with Koss esp-9 earphones. The input is a 1-3khz band-pass filtered impulse.

Figure a: Left earphone
Figure b: Right earphone
Figure c: Electrical input.

can be found in terms of the transduction process from electrical input to air pressure output. However, one notes a difference between the input and output waveform, particularly on the second undershoot; this is due in fact to a small resonance of 3 db at about 3 khz on the headphones characteristic curves. (See Fig.III.9) It must be emphasized that this particularity of the transduction process is common to the two headphones and the resulting difference between these two is consequently less significant.

The tests whose results have been reported here were not specifically aimed at evaluating the performance of the earphones as acoustic transducers: this would require a different technique[1], using specially designed couplers and acoustic cavity, in order to obtain curves comparable to figure III.9. The tests were carried out so as to give an idea of the degree of similarity of the acoustic output of the individual phones as well as to visualise and characterise the particular type of acoustic transient used in our experiment.

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1) The technique is described in detail in Koss Electronic, OM-125, operating manual, p.4.

III.4 Bekesy Audiometric Test

The audiometric technique originally developed by Georg Von Bekesy, became soon after its discovery a universally accepted method for determining psycho-physically the threshold of hearing at various frequencies. This audiometric test uses a variable frequency signal, logarithmically swept from 100 Hz to 10000hz during a period of seven minutes. The subject is asked to keep a continuous tracking of the signal at the threshold level, by pressing or releasing a control that correspondingly increases or decreases the amplitude of the signal.

In order to ease the comparison from one subject to another, the results of the Bekesy's audiometer are not usually presented as a measure of the absolute threshold of hearing, but rather as the deviation from an idealized human auditory threshold function, taken as a zero db. line. In the present case, such a function is labelled: "ISO 1964 Value". An ideal audiometric measurement, would then report a straight line, superimposed by a sawtooth waveform corresponding to the continuous tracking of the threshold. A typical Bekesy measurement is presented in figure III.14.

We have performed a test of this kind on six of the subjects who collaborated in nearly every experiment reported in the present work. The tests were part of an otological examination that subsequently confirmed that they all had normal hearing.

We present here the results of these tests in a slightly different form; for every subject, the curves like the one in figure III.14, were digitized on a computer and subsequently filtered with a technique that we will discuss in a later section. The filtered version of the audiometric test is presented in figure III.15

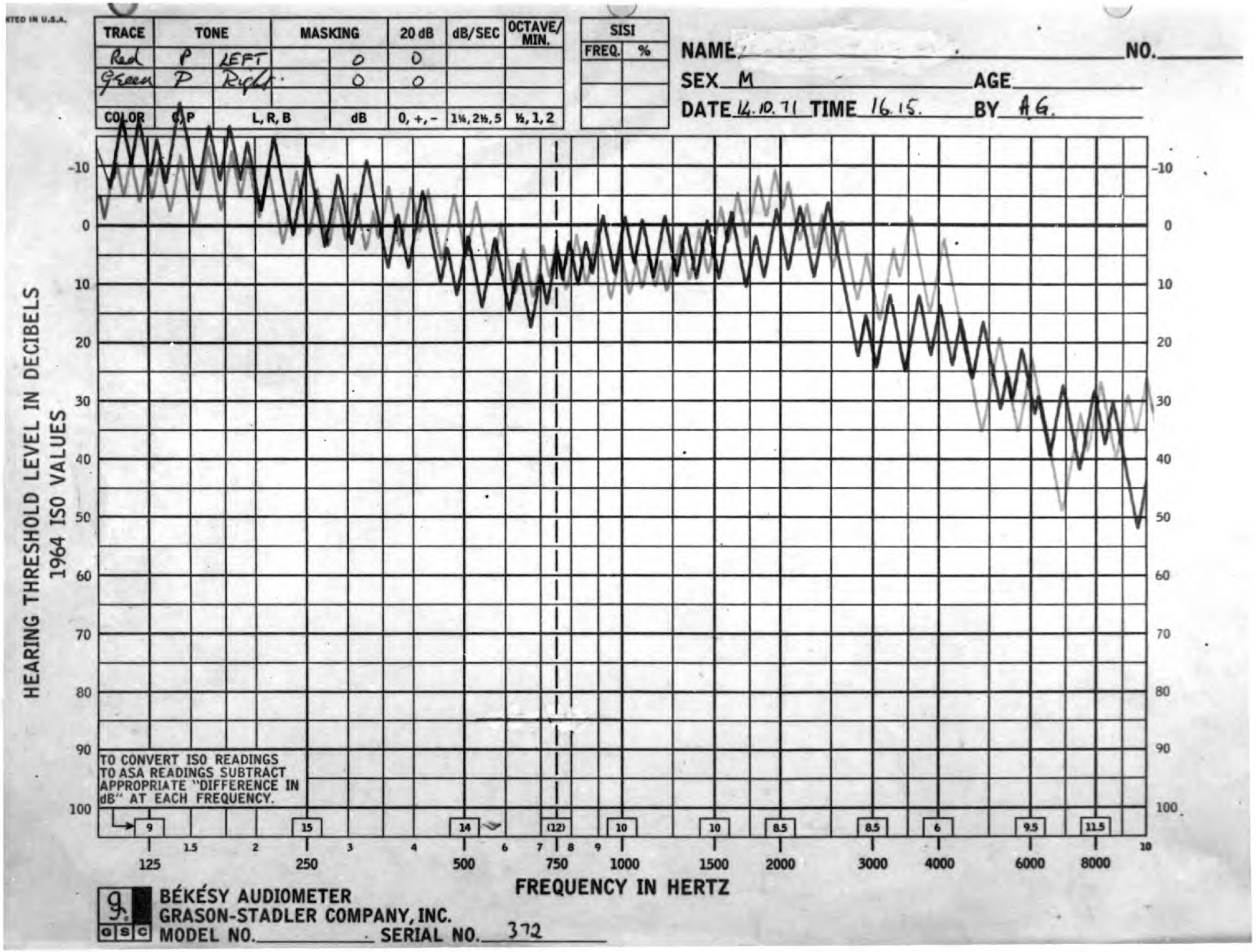
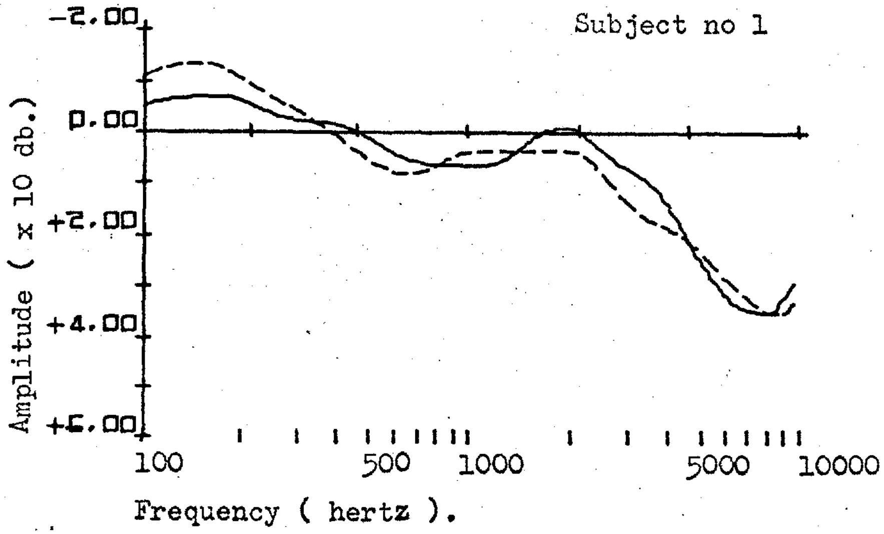


Figure III.14. A Bekesy audiometric test report.



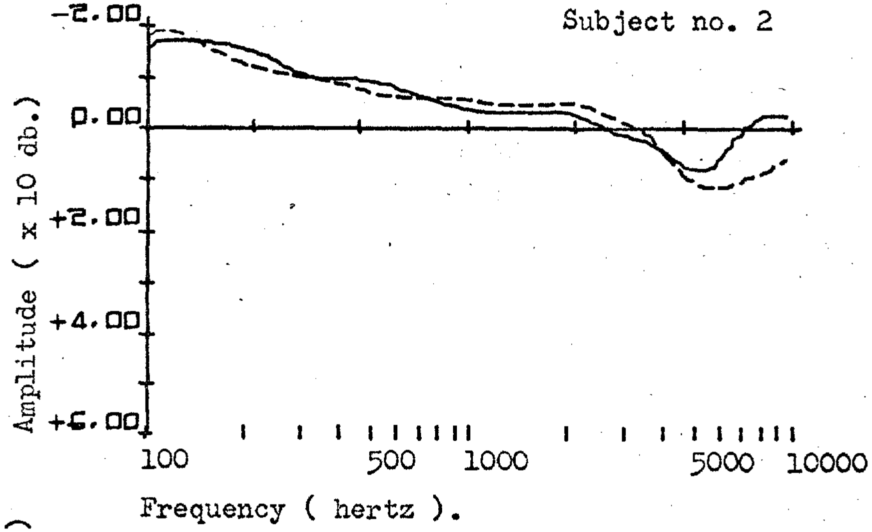
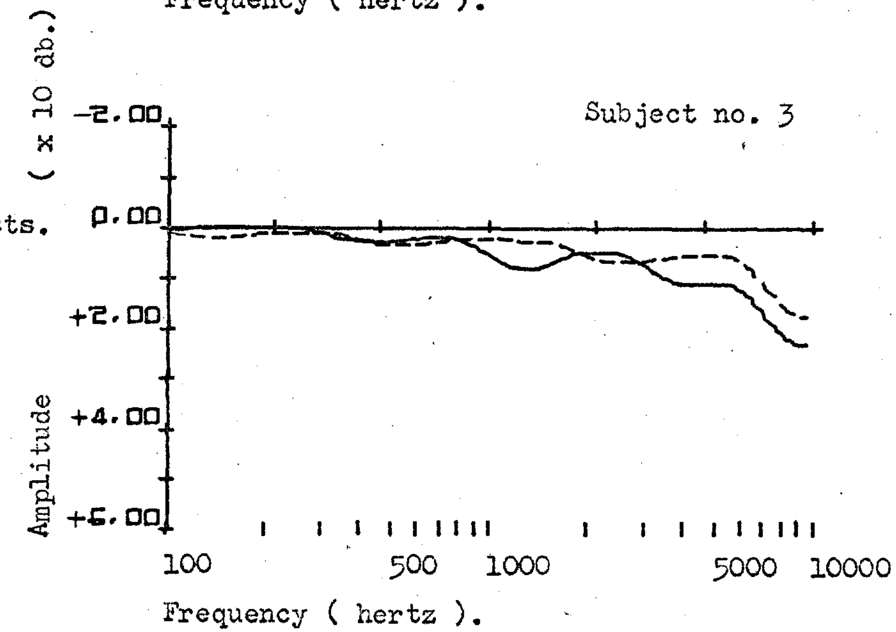
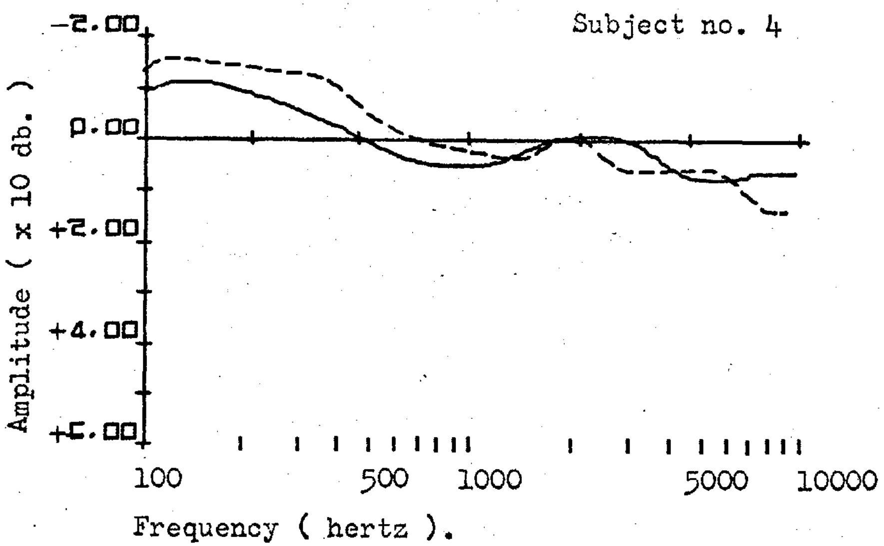


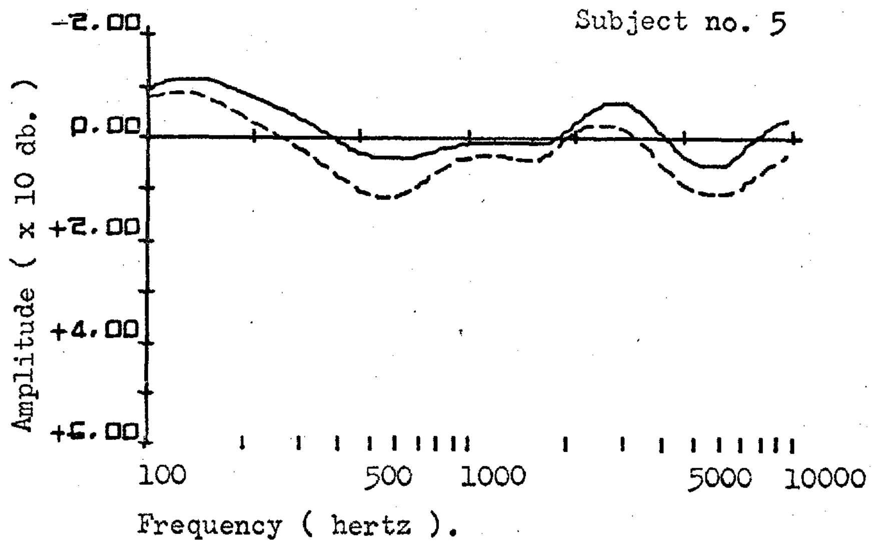
Figure III.15. Filtered Bekesy audiometric tests.

- - - : right ear.

———: left ear.







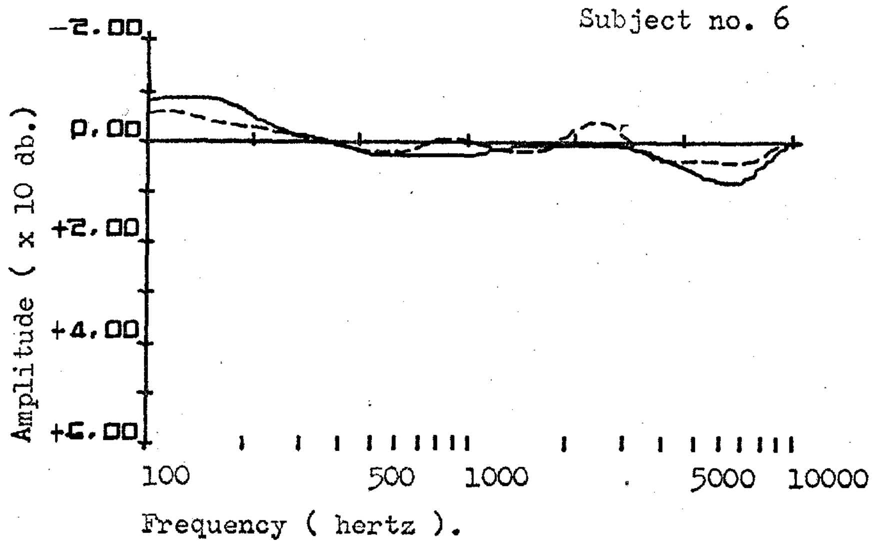


Figure III.16 Filtered Bekesy audiometric tests.

- - - : right ear.

——— : left ear.

and III.16 in which the subjects are identified by numbers from 1 to 6, as they will be consistently in every result presented in the course of this work. This type of signal processing is intended to clarify the presentation of the audiometric test; it enables easier comparison to be made between the various subjects as well as between their individual monaural performances.

In a previous section we discussed the importance of using a matched pair of headphones in a binaural experimentation procedure; the discussion would apply equally well in this section, to stress the importance of using subjects with binaurally balanced auditory sensitivity.

Undoubtedly, five of our subjects would comply with this requirement, since their individual sensitivity curves match within 6-7 db. As for the remaining subject (S-4), a close examination of his performance has shown that the 10 db. sensitivity difference at 400 hz, was a consequence of a training process in doing the audiometric test: the left ear being tested first, a certain amount of training was then made available for the test of the right one, resulting in an apparent improved sensitivity. A partly re-run test of this subject, has in fact confirmed this hypothesis.

A last observation to be made concerns the variation from one individual to another of the threshold of hearing. Individual psycho-physical measurements reported in the present work are very often grouped together and analysed as if they were taken from a single statistical population. It is relevant to the present section to see whether or not such an assumption is valid, at least in the light of the individual sensitivity curve provided by the Bekesy audiometer.

At the low frequency range, the largest inter-subject sensitivity difference is between S-2 and S-3: more than 15 db. at 100 hz. The question of assigning the significance of this difference, is in this particular instance, a very difficult one. It must be remembered that the Bekesy's audiometric test is a psycho-physical measurement; therefore quite a large variability between subjects may be expected as a consequence of psychological factors such as motivation, attention, rapidity of reaction, etc. The peak to peak value of the sawtooth waveform gives an idea of the degree of variability introduced by those parameters: figure III.14 shows this value to be in the order of 10 db. From this we can conclude that the 15 db. difference between S-2 and S-3 is much less significant than it would seem a priori, and that probably the thresholds here mentioned, differ effectively only by a few decibels.

As far as the high frequency is concerned, only subject 1 could cause some difficulty. However, in the present study, we report experiments performed with transients low-pass (or bandpass) filtered below 3 khz. Therefore, the high frequency loss of S-1 is not likely to cause any problem.

III.5 A Computer Monitored Binaural Experiment

Psycho-physical measurements have this in common, that they all attempt to quantify objectively, behavioural performances that, themselves originate subjectively. As a result of the complexity of the mechanisms involved, such measurements are, on the whole, bound to be noisy and, in general, successive averages are necessary to give acceptable level of confidence. On the other hand, the mere fact of repeating a behavioural trial for a prolonged period of time, can itself introduce additional factors of noise to the related measurements, and would therefore go against the purpose of the exercise. For that matter, the idea of using an automated experimental technique is very attractive: it has the strong advantage in achieving more reproducible results since it utilizes more effectively the usable period of a listener attention. The Bekesy's audiometric technique is an example of a successful application of this principle.

Historically, there are many examples to illustrate the use of a similar approach to binaural experimentation. Bekesy,(1960) reported on an automated experimental procedure where a paper tape system was used to program some 3000 lateralization presentations and record the corresponding judgements. More recently Toole, (1965), described in detail a system using a multi-channel magnetic tape, where the experimental protocol for lateralization presentation was pre-recorded; in this example, the actual data acquisition was also done with a paper tape system. Following the same line, we detail here an up-dated version of those various techniques, using a process control computer in conjunction with the programmable pulse generator described in Section III.3.

We recall here that in the course of this work, we will report results from automated centring experiments (see Section III.1), where the parameter used to evaluate a subject's performance is the inter-aural time difference (I.T.D.). Figure III.17 illustrates the principle of our method.

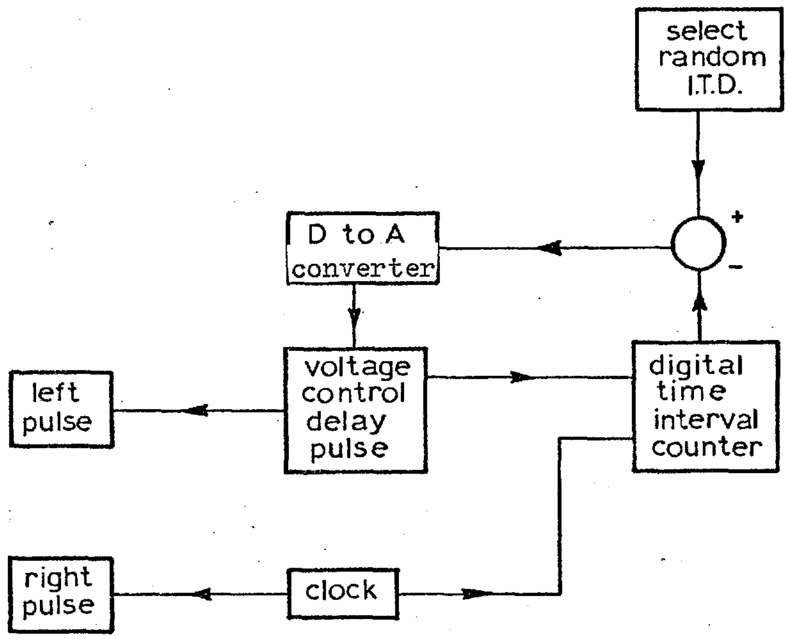


Figure III.17 Block Diagram of the system generating a computer programmable delay

Basically the system is made of a digital time interval counter, measuring the time difference between a start and a stop pulse, respectively the right ear and the left ear pulse. A random value of inter-aural time delay is selected and compared to the value displayed on the counter and read by the digital input of the computer. The difference between those time values is then converted into a voltage that controls the programmable pulse generator. The system will adjust until the counter shows the correct value, corresponding to the desired I.T.D.

In the practical realisation of this system, we had however to introduce another important element in this converging loop. In order to be able to evaluate the corrected voltage that would tend to null the difference between the selected and the displayed I.T.D., one must provide the system with an approximate calibration curve giving the relation between the number fed to the D. to A. converter and the corresponding generated delay. In other words, if the time interval counter displays a value that differs by 100 µseconds from the selected I.T.D., the computer must be able to estimate by how much the D. to A. value has to be altered to reduce the original time difference. Therefore, previous to the experiment, a calibration curve of the form:

$$\text{D. to A. value} = C_0 + C_1 \cdot \text{delay} \qquad \text{equation III.1}$$

was computed from a least square fitting algorithm. Subsequently the C_1 coefficient was used to estimate the correction to which we are referring.

As mentioned earlier, the computer was used not only to do the actual click presentation by controlling the loop of figure III.17, but also to monitor the complete experiment. It would, for instance, continuously record the dynamic centring judgements, and perform sequential function-like muting, measuring resting period as well as the time taken to perform a judgement, inverting the headphones etc. Figure III.18 gives a simplified block diagram of the way this is achieved.

Using this automated system, we were able to study some 10,000 binaural judgements that, otherwise, would have been nearly impossible to obtain and subsequently handle. As later chapters will show, it has also enabled us to take a new look at some more familiar results from which original conclusions can be drawn.

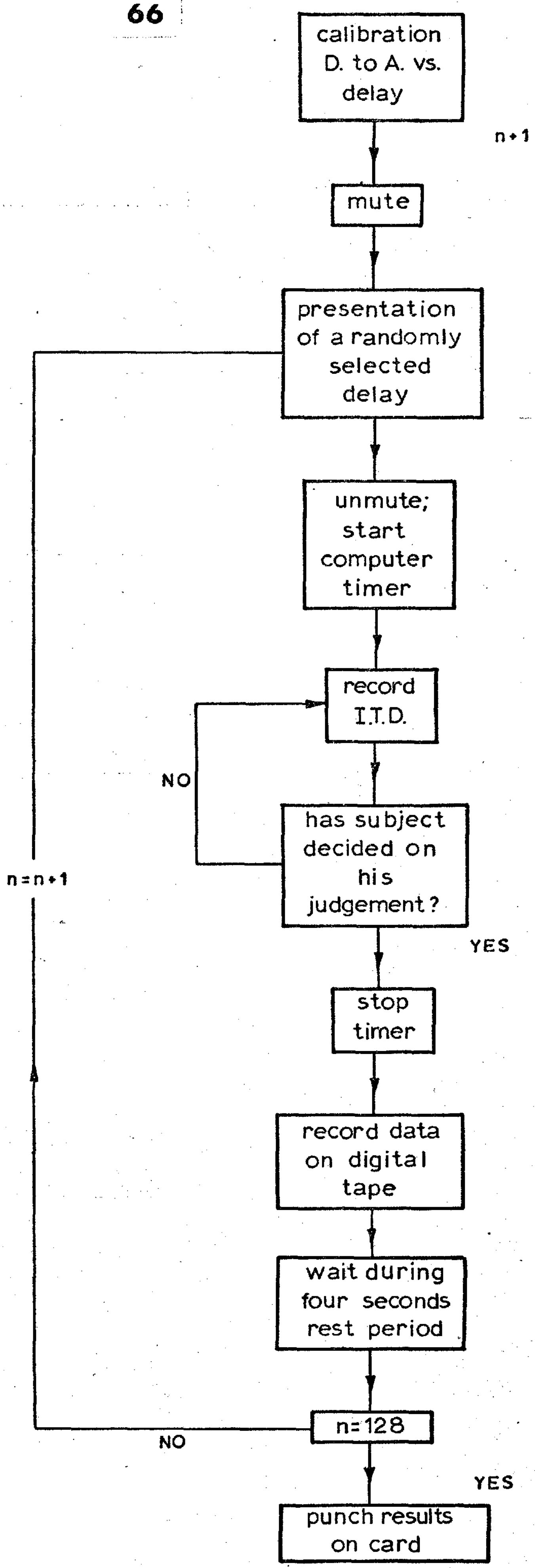


Fig. III.18. Block diagram for a binaural centring experiment

III.6 A note on Signal Processing: the design of an autoregressive digital filter

On many occasions along the course of this work, we will refer to a particular method of signal processing, namely the autoregressive digital filtering technique. This topic will be briefly discussed here, but for a detailed review of the subject, the reader is referred to a report by Lynn (1969B).

In the autoregressive digital filter, the output is calculated not only from input samples, but also from previous output samples. The very important advantage of this operation is that, in many cases, the recurrence relationship that describes the filter, is from the point of view of computer realisation, much more economical than its corresponding non-recursive expression.

A zero phase low-pass filter that we will frequently refer to, is described by the relation:

$$Y(n) = Y(n-3) - 3Y(n-2) + 3Y(n-1) - X(n-3k-3) + 3X(n-k-2) - 3X(n+k-1) + X(n+3k) \quad \text{equation III.2}$$

where Y(n) and X(n) are respectively the present output and input samples.

The cut-off frequency of this filter can be selected by altering the corresponding value of k: the frequency response zeros at 1/ (2k+1) of the sampling frequency. Figure III.19 illustrates this point by showing the impulse response of the present filter as well as the frequency response curve for three values of the parameter "k".

We must emphasize here that this type of filter would not be physically realisable, since the present output necessitates the knowledge of some future inputs e.g. x(n+3k). When a filter of this kind is used in an autoregressive form, it is essential to ensure that the filtering process is properly initialized: a past history of outputs must be computed. The following example will illustrate this point.

As seen from figure III.19, there is a non-zero output from the filter even before any input signal has been applied; in other words, taking X(0) as the first non-zero input to the filter, Y(-1) and Y(-2) in equation III.2 would not be zero and must therefore be computed since they are to be used to find Y(0). Inspection of equation III.2 shows that in fact it is necessary to go back as far as Y(-3k-1) to finally obtain a non-zero output.

Similarly band pass and high-pass recursive realisation can be achieved, for which the previous considerations apply equally well. Some interesting zero-phase, integer coefficient autoregressive relations applicable to these particular cases will also be found in the paper of Lynn (1969B).

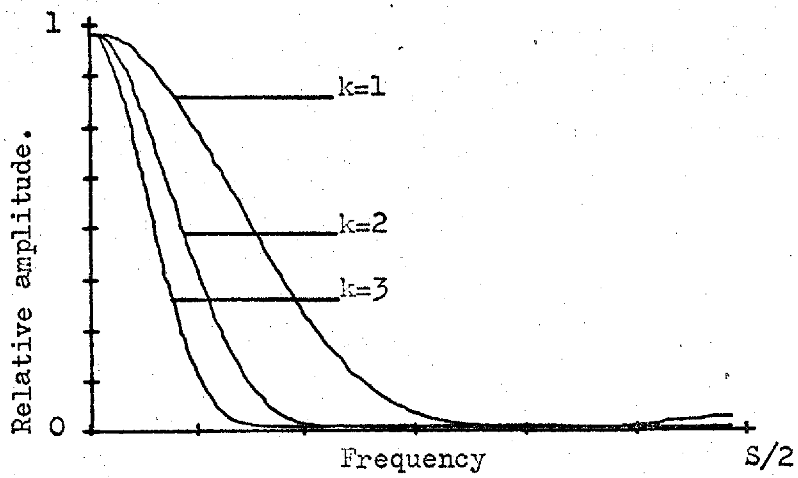


Figure III.19 a.

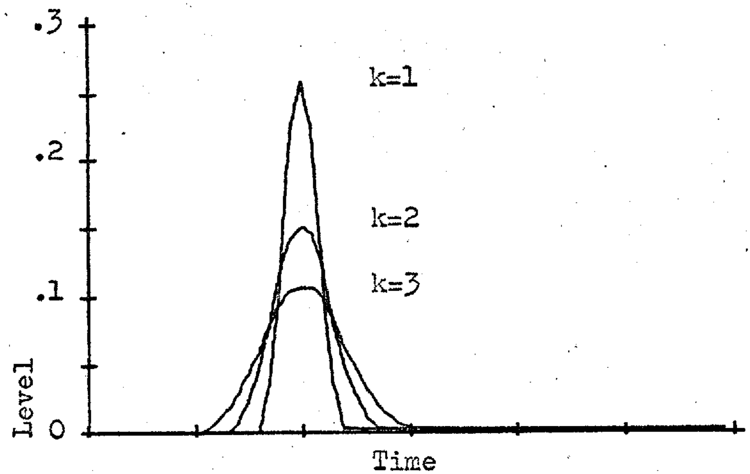


Figure III.19 b.

Figure III.19. Responses of the autoregressive digital filter described by the equation:

$$y(n) = y(n-3) - 3y(n-2) + x(n-3k-3) + 3y(n-1) + 3x(n-k-2) - 3x(n+k-1) + x(n+3k)$$

where y represents the output, x the input.

Figure III.19a: Frequency response; S is the sampling frequency.

Figure III.19b: Impulse response.

Figure III.19c: Input signal.

The responses are presented for three different values of "k".

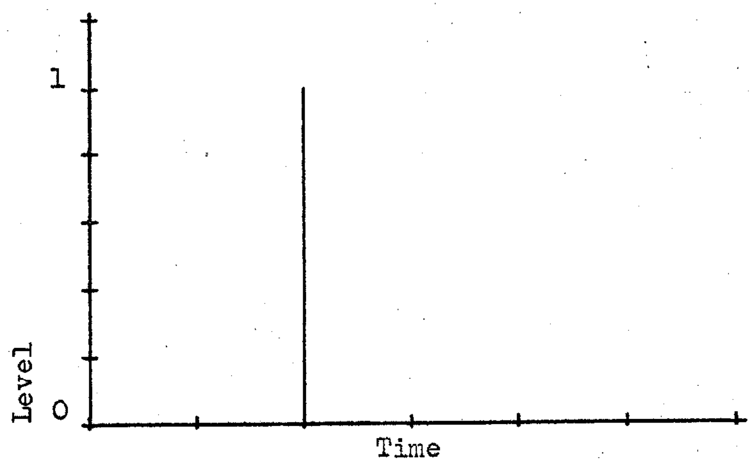


Figure III.19 c.

CHAPTER IV

EXPERIMENTAL STUDY ON THE BINAURAL INTERACTION OF SIMPLE TRANSIENTS WITHOUT I.A.D.*

IV.1 Introduction

The purpose of this chapter is to characterize the binaural centring judgement process, from the data obtained with the experimental technique described in the preceding chapter. It is intended to do this using two different approaches.

The first method studies in detail the judgement corresponding to centred images while investigating the fine structure of the judgement distribution obtained experimentally. The distribution is compared with the predicted perceptual behaviour obtained from modeling binaural interaction, by cross-comparing the neural activity which emanates from corresponding sites in the two cochleae. (Monro, 1971).

The second approach investigates the dynamics of centring an acoustic image since it seems possible that dynamic aspects play a significant part in the centring process. Using system analysis techniques, the result of this investigation will enable the modeling of a system in which the human operator is the key element; furthermore, it should permit the use of binaural experimentation in future ergonomic studies.

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*Low pass filtered at 2 khz,75 db. peak sound level, 20 per sec.

Both methods have this in common in that they lead to a quantitative description of the binaural interaction of simple transients, thus allowing further work on the interaction of more complicated waveforms to be compared, on a quantitative basis, to the present one.

IV.2 Statistical Study on the Distribution of Binaural Centring Judgements.

IV.2.1 The Distribution of Binaural Centring Judgements.

Figure IV.1 (a and b) shows the set of histograms* of groups of 128 binaural centring judgements recorded with the six subjects previously mentioned; a representation that eliminates the individual variation is given by building up a single histogram from the whole set of judgements (768 judgements) as if they were taken from a single population; this is presented in figure IV.2, where a normal distribution has been fitted to the data.

A first observation to be made on this particular set of data, concerns the modality of the histogram; as far as a bin-width of 30 microseconds can resolve, (15 μsec. in the case of figure IV.2), the various histograms can be described as unimodal, i.e. they are identifiable by a single maximum; this is particularly obvious in figure IV.2, where a greater number of data enabled construction of a smoother histogram. Superficially, this finding seems to contradict other work. For example, according to a current view on the mechanism of binaural interaction, as proposed by the model of Monro (1971), multiple acoustic images should arise from interaction of even simple,

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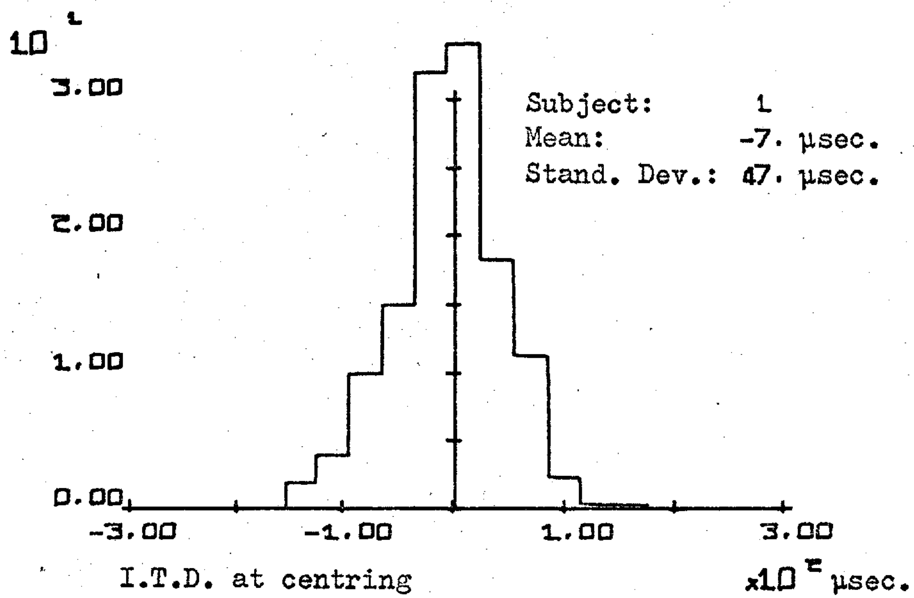
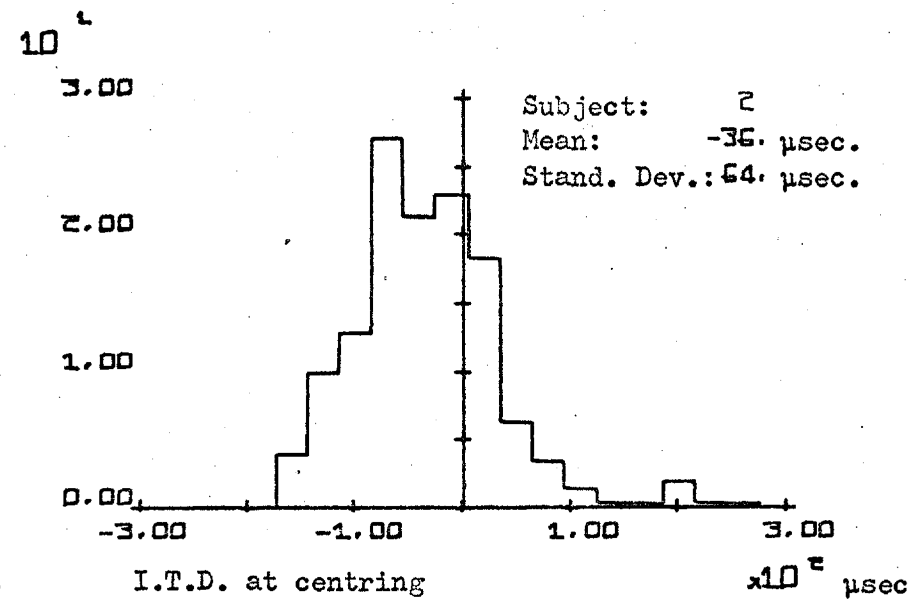
* Positive values of I.T.D. define left leading pulse.





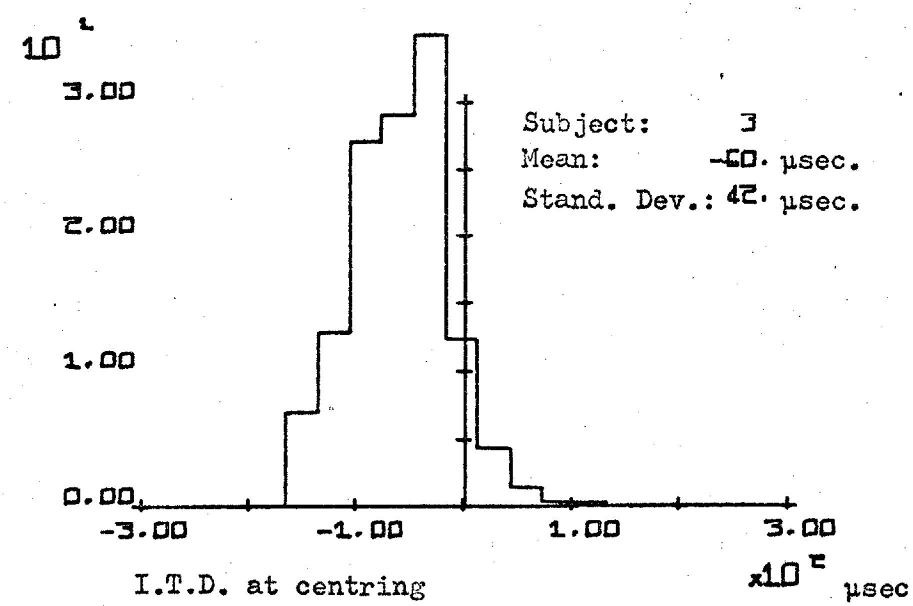
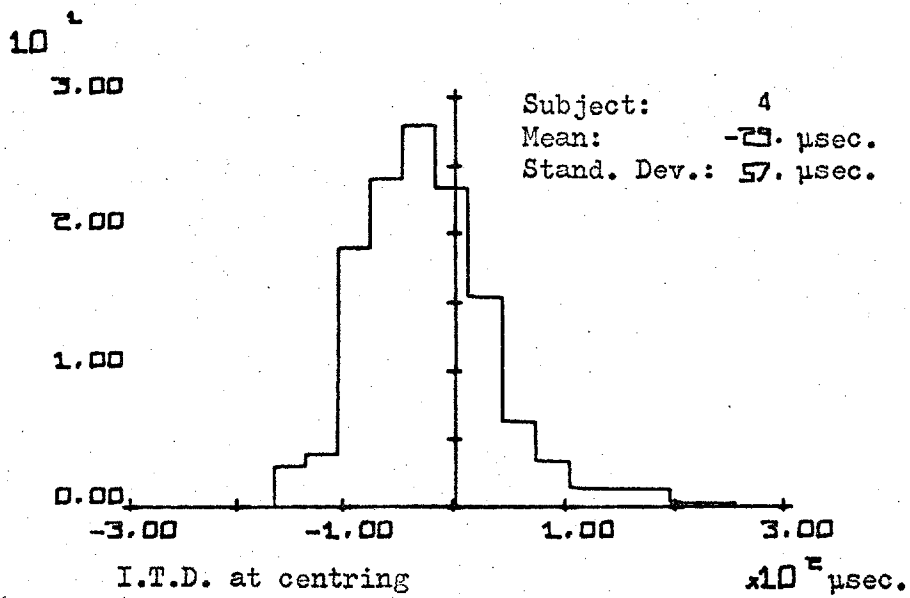
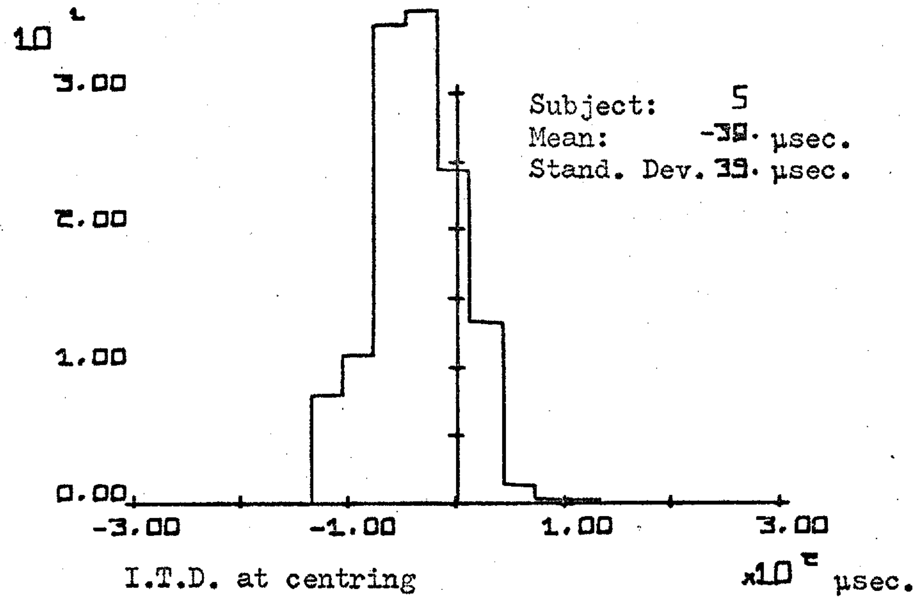


Figure IV.1 a. Binaural judgement histograms for individual subjects. Centring of simple clicks without I.A.D.





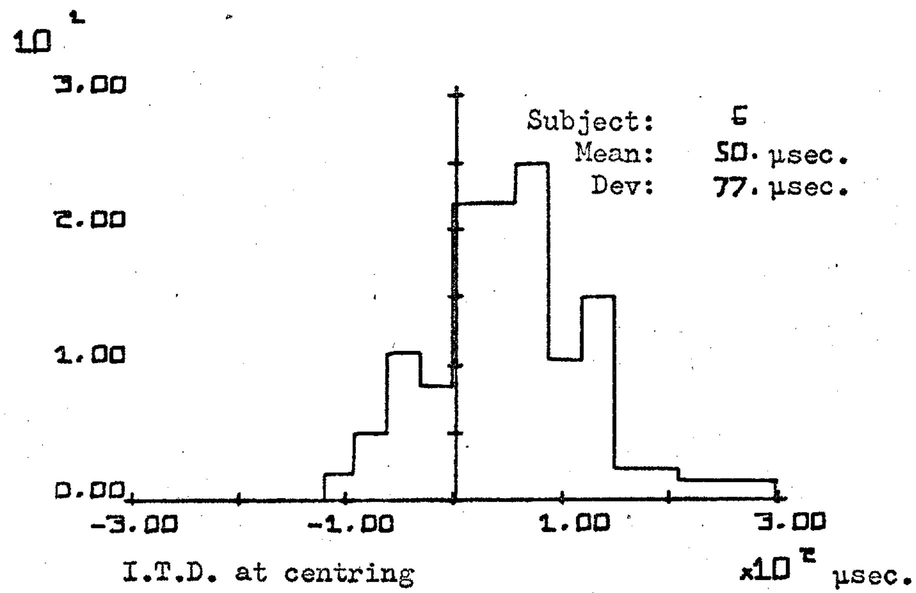


Figure IV.1 b. Binaural judgement histograms for individual subjects. Centring of simple clicks without I.A.D.

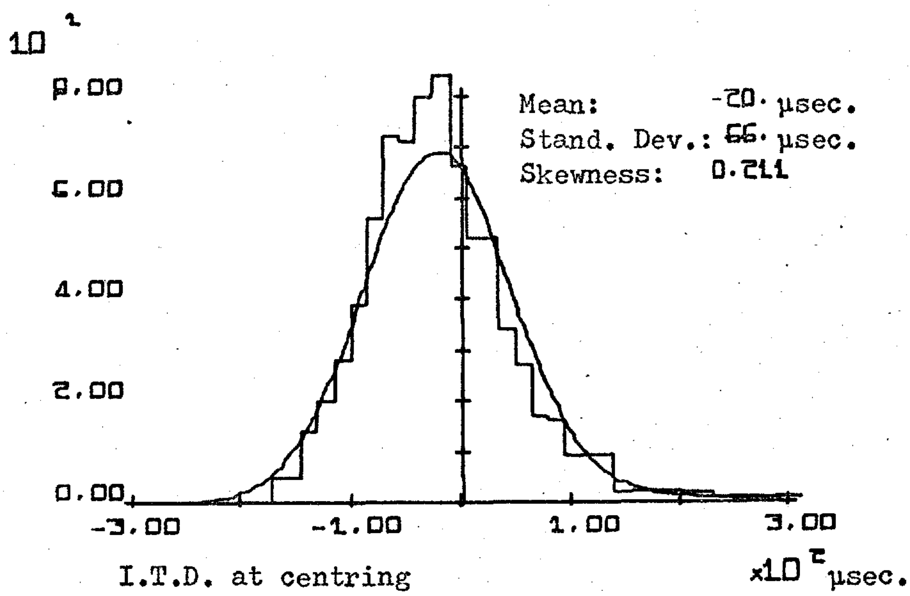


Figure IV.2. Binaural judgement histogram, showing the distribution obtained by combining the individual data of figure IV.1 (a and b) .

single auditory clicks. As explained earlier, this would be a direct consequence of peripheral transformations imposed, on the acoustic waveform, at the basilar membrane level. Indeed, the basilar membrane response to a single click, exhibits several rarefaction displacements, perhaps three or four, which in turn may give rise to a number of corresponding peaks in the post-stimulus time histogram as recorded from a single auditory nerve fiber. A mechanism of binaural interaction based on a cross-comparison of neural activity emanating from corresponding cochlear loci, would consequently generate multiple binaural images, possibly one for each peak of the P.S.T. histogram.

According to this view, it should be possible in centring experiments to have the images independently centred; clearly the definite unimodal character of the binaural judgement distribution indicates that such a situation does not happen, i.e. the images are not perceived as multiple.

This experimental evidence does not, however, pretend to cast doubts on the validity, or the pertinence, of the binaural interaction model referred to earlier; in the view of this model, and in the light of the experiments on the binaural fusion of simple auditory clicks reported here, we propose that amongst the multiple images present in the acoustic field, the dominant one succeeds very effectively in masking its concommitants. The extent of this masking is to the point where the other images are, most probably, not perceived; for amongst the 768 binaural judgements, none of them were judged outside the range: $\pm$ 300 µsec. In the experiments reported here, it is recalled that the clicks are transients low-pass filtered at 2 khz, and consequently little activity should arise on basilar membrane points of corresponding higher place frequency; in such a situation, the multiple images predicted by the model of cross-comparison of neural activity from corresponding membrane place, should be spaced by at least 500 μsec., (1/2 khz)[1]. The standard deviation of the distribution of figure IV.2, being in the order of 66 μsec., would definitely permit to resolve two peaks spaced by 500 μsec, nearly 8 times the standard deviation. It is therefore necessary to conclude in the light of the experiments reported here that, in broad terms, any secondary images arising are masked in this experimental situation, and that, in all probability, they are masked completely.

Additional remarks relating to the statistical distribution concern the value of the mean and the skewness of the histogram. A simple test of hypothesis on the mean, would show that a mean of -20 μsec., computed from a set of 768 samples with a standard deviation of 66 μsec., is different from zero at a .002 level of significance. As far as the skewness is concerned, it is evaluated at .21 by the Pearson's second coefficient which indicated that the distribution is asymmetric with respect to the mean. At first sight, these facts are rather surprising since the mean, and the skewness, are expected to be around zero value. This might be due to a population bias enhanced by the fact that only six subjects were used; however, this is most unlikely, since five out of the six subjects produced negative average judgements.

It is believed that this unexpected asymmetry is rather due to a bias introduced by the headphones themselves; figure III.9 has shown the left earphone to be 2 db more sensitive than the right

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[1] In other words no significant image should arise from place frequency $>$ 2 khz.

one. Therefore a nominal[1] inter-aural amplitude difference of 0 db, will be perceived as an I.A.D. of +2 db; it will be shown in a later section that binaural centring, with I.A.D, is associated with a shift in the centre of gravity of the centring judgements histogram. The order of magnitude of the shift reported here (20 µsec) would also be consistent with the view that an I.A.D. of 2 db is being perceived. For the present moment, it is sufficient to state that the measure of asymmetry of the histogram, and the shift in the centre of gravity, are consequences of the slight asymmetry at the level of the acoustic input.

IV.2.2 A Correlation Analysis of Binaural Judgements.

The picture drawn by the binaural judgement population histogram is certainly not sufficient to describe completely the process that we are now studying; although it is informative on the sample distribution, it does not provide much insight on why it is distributed in any particular manner. Is the error signal present in a binaural centring judgement the outcome of a totally aleatory process, or does it contain some deterministic features? In an attempt to clarify this point, hence to provide additional informations on the mechanism underlying binaural fusion, the following analysis is presented.

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[1] In the experiments reported along the course of this work, it is understood that the values of I.A.D. are nominal values of acoustic input since they refer to the electric input applied to the headphones. An I.A.D. of 0 db is heard as an I.A.D. of 2 db.

We first want to examine if the value of the randomly selected I.T.D. at the time of presentation of the transients, has any bearing on the subsequent binaural centring judgement, or, in other words, if binaural images are centred differently following any particular initial presentation. For that matter a scatter diagram of the judgements is at a glance quite illuminative.

Figure IV.3 shows the complete set (768) of judgements plotted versus the I.T.D. initially presented; the latter variable, it is recalled, has been generated by a computer from a pseudo-random generator. Figure IV.4 presents the same data in a different form: here, the horizontal axis in the diagram (figure IV.3) has been equally divided in 15 bins, the content of which has subsequently been averaged with respect to both coordinates. The individual averages, and their corresponding standard deviations, are presented on the figure. The 95 per cent confidence intervals have also been computed, and are shown as the upper and lower limit of the function.

Observation on these two figures indicates that the judgements are scattered independently of the input I.T.D., for which therefore in the range considered, there is no preferred value. This fact argues in favour of the view supported in the previous section on the effective masking of secondary images: if for any particular value of input I.T.D. other images were initially perceived, their effect would be to alter the mean of the corresponding centring judgements and/or increase the associated standard deviation. The first effect would arise when the secondary image is itself centred, while the second case would occur as the image renders the centring more difficult by, for instance, enabling a continuous shift of attention between the two images. The constant level of standard deviation (figure IV.4) throughout the range of input suggests that

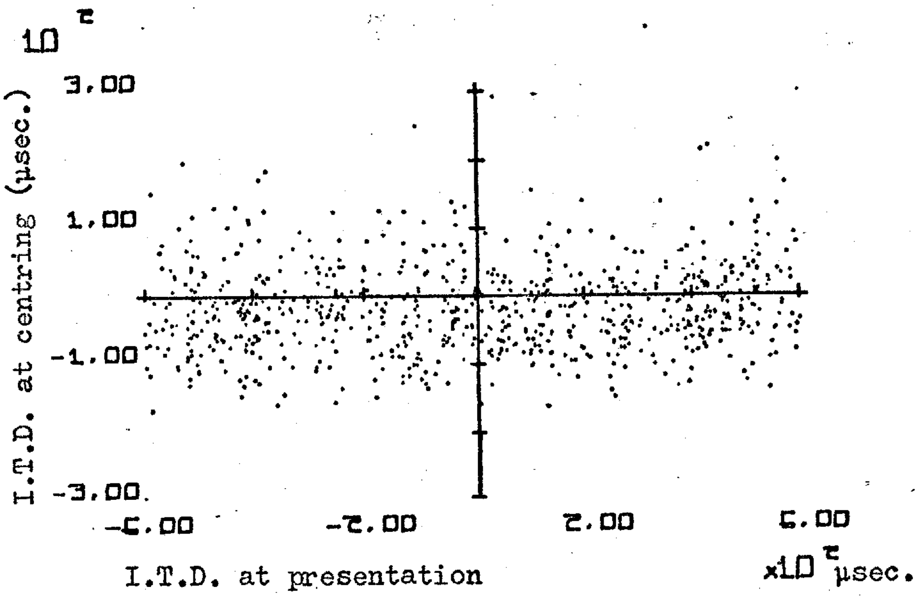

Figure IV.3. Scatter diagram of centring judgements versus initial I.T.D.; single clicks, I.A.D. 0 db, 6 subjects, 768 judgements.

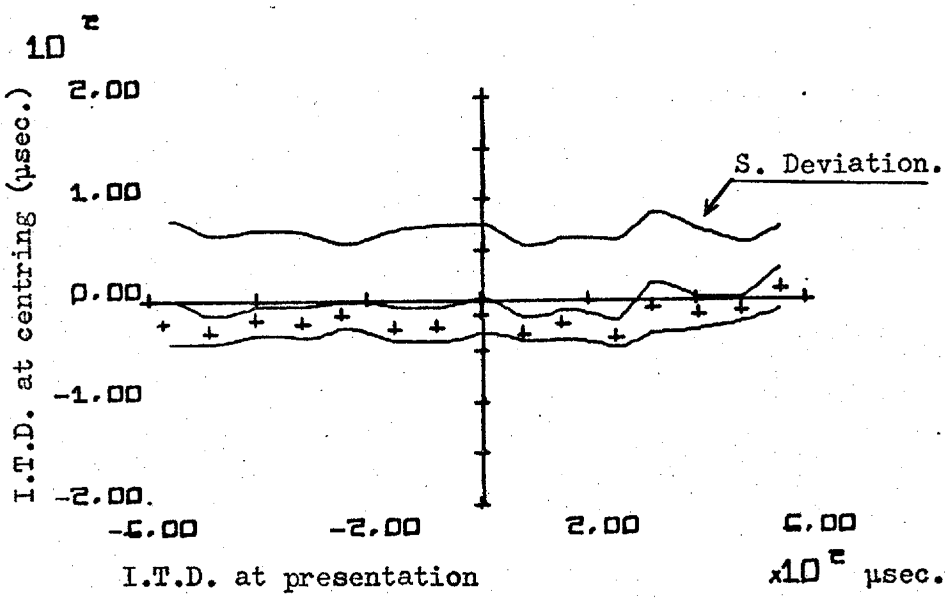

Figure IV.4. Averaged scatter of figure IV.3

such an effect does not occur. As far as the various means are concerned, the presence of any secondary images could not be detected in the relatively fluctuation-free waveform that they generate.

Similarly, as suggested by figure IV.3/4, the results reported here would not favour any correlation between input I.T.D. and centring judgements. A statistical correlation coefficient of .07 was computed for the samples under study and could not be found to be significant from zero at a .03 level of significance.

To consider the possibility of non-linear correlation, the matter was further investigated using the following method: the various binaural judgements were grouped according to their corresponding I.T.D. presentation. Four classes of input were examined: -600 to 300 µsec I.T.D., -300 to 0 µsec I.T.D., etc., up to +600 µsec. The histograms of the centring judgements belonging to the individual classes of input are presented in figure IV.5.

Again the previous observations are evidenced very clearly: a quasi-constant level of standard deviation of 66 µsec. is found in the four histograms, while the mean levels are not significantly different from each other. However the measure of skewness does not seem to be correlated so simply to the I.T.D, effectively being higher for both positive and negative extreme values of I.T.D. Nevertheless, this later matter is not so easy to discuss in this particular instance since each histogram is built up from approximately 180 judgements; this is a rather small number of samples when it comes to infer significance about morphological differences between various histograms, and we therefore will not attempt to be speculative on this point.

In short, it can be stated that, in the case of the interaction of simple auditory clicks, no significant correlation exists between

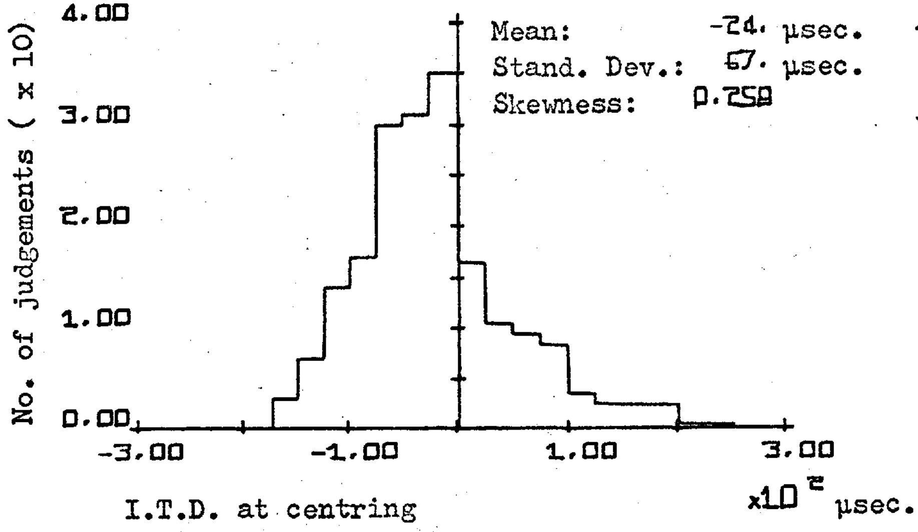

Figure IV.5 a. -600 to -300 µsec range.

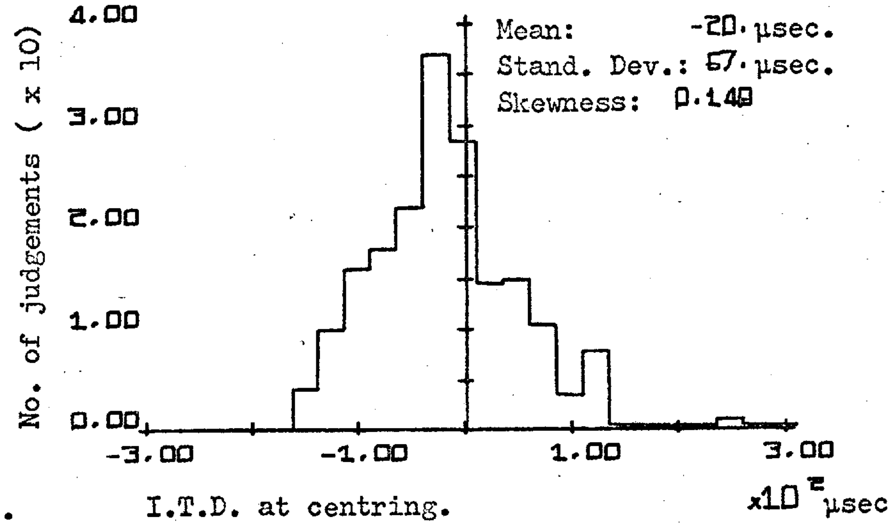

Figure IV.5 b. -300 to 0 µsec range.

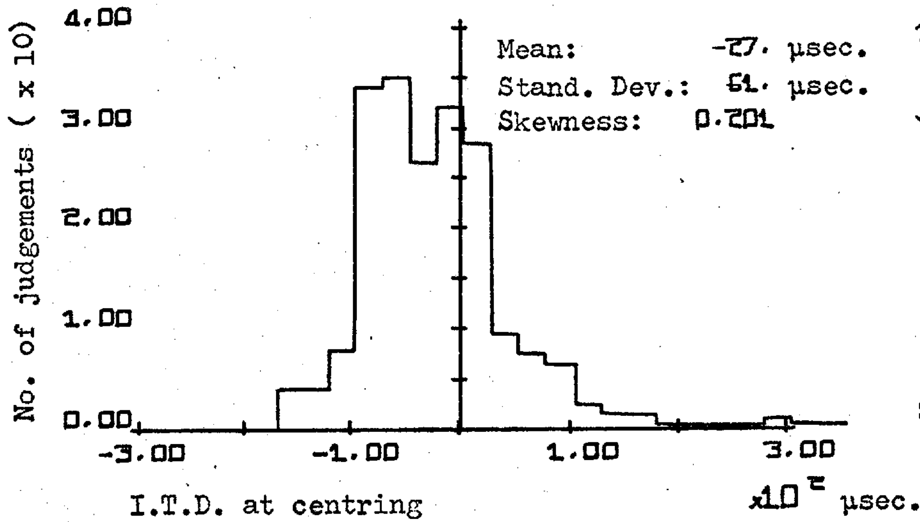

Figure IV.5 c. 0 to 300 µsec range.

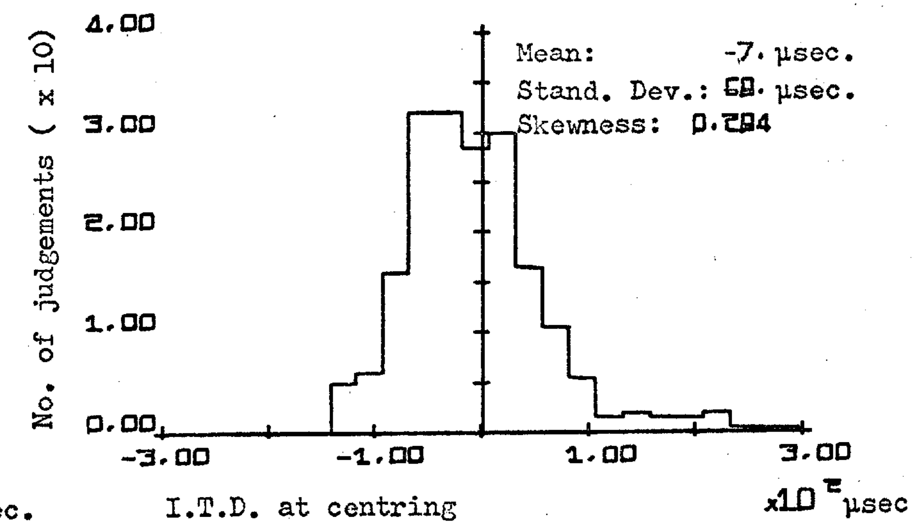

Figure IV.5 d. 300 to 600 µsec range

Figure IV.5. Binaural judgement histograms; the judgements have been grouped according to the initial I.T.D.

the originally perceived image position and the finally centred judgement. Similarly, the presence of secondary images, correlated to any particular I.T.D. in the range considered, could not be detected.

Having examined the possibility that the binaural centring process might be influenced by the value of the I.T.D. at the time of presentation, we now turn to the point where we want to determine if the time taken to perform a binaural centring, is in any way related to the image, judged as centred.

The scatter diagram in figure IV.6a shows the set of 768 judgements plotted versus the time taken to perform their respective centrings. Visual inspection indicates that there is no correlation between the two variables; indeed a linear correlation coefficient computed from this set of data as .08, would not be different from zero at the .03 level of significance.

There are indications however to suggest that a form of non-linear correlation exists between the two variables: figure IV.6b is a plot of the standard deviation of the centring versus the time taken to perform a judgement. It is observed that the standard deviation decreases as the time to perform a judgement increases, and this at a rate of 2 µsec/sec of judgement. It could therefore be concluded that as the time of centring increases, the subjects produce more consistent results.

It therefore appears that, although not directly involved in the centring mechanism, the time to perform a binaural centring judgement (using simple auditory clicks, I.A.D. = 0) is not totally irrelevant to the process. Being directly related to the standard deviation , while remaining uncorrelated with the mean of the distribution, it however does not suggest that multiples binaural images are perceived.

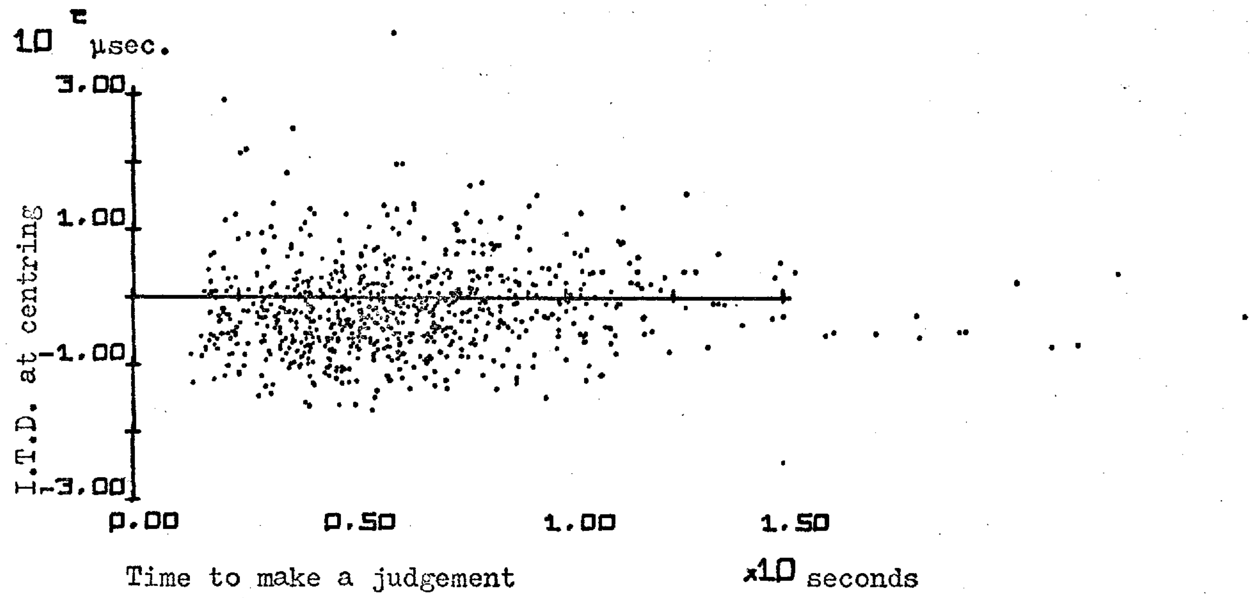

Figure IV.6 a. Scatter diagram of centring judgements versus time to make a judgement; I.A.D. Odb, 6 subjects.

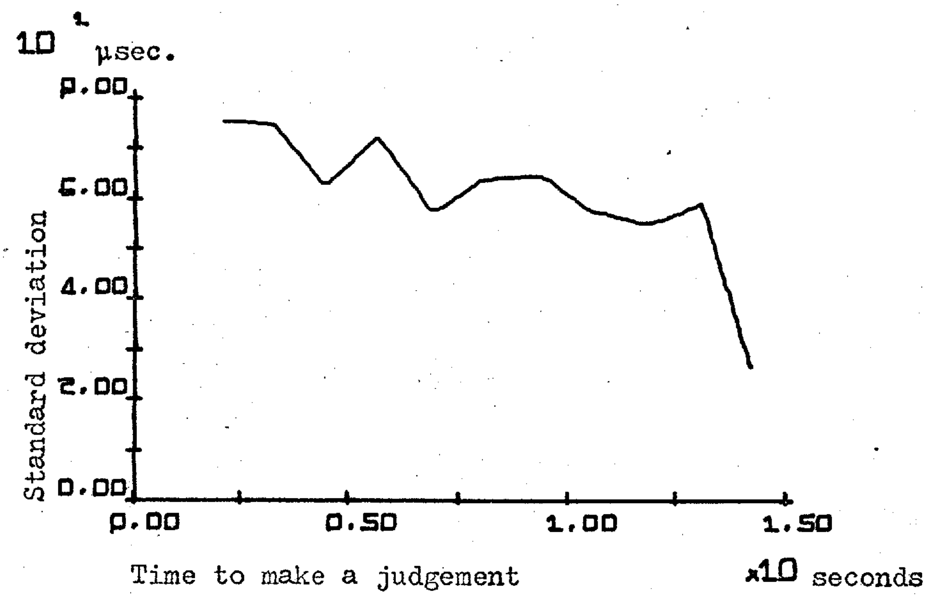

Figure IV.6 b. Standard deviation of the centring judgement distribution versus time to make a judgement. Same experiments as in figure IV.6 a.

A general conclusion that could be drawn from the analysis presented here, is that the error signal associated with binaural centrings, does not contain any deterministic features as far as the initial I.T.D. is concerned; similarly, indications are that the time to perform a centring does not influence the average centring, although it may contribute to reduce the amount of noise present in the signal. There is also no evidence from this correlation analysis, to support the view that multiple coexisting images are perceived in this experimental situation.

IV.3 The Dynamic Centring Judgement Process

IV.3.0 Introduction

Previously we have considered the binaural judgement only as the end product of a still largely unknown, complex mechanism; a randomly positioned image was presented and centred, and it was this finally centred image, envisaged as an event, that we have been analysing quantitatively in detail. An analysis of binaural judgements would not be complete, or realistic, if it limited its interests to the eventuality of a centring and did not look at the dynamic operation preceding any particular judgement; as pointed out earlier, (Chapter III, figure III.5), a centring judgement is the result of a dynamic process involving some 5 to 8 lateralization decisions ultimately converging to the recorded centred image. It is believed that this human operation which occurs between original presentation and centred position, plays an important part in the way binaural perception is achieved (or expressed?) at least in the context of binaural experimentation. We therefore intend at this stage to present a detailed analysis of what could be called the binaural judgement dynamic.

IV.3.1 A Linear System Approach to Binaural Experimentation

However simple the results of binaural centring may seem the actual operation of performing a positional judgement of this sort out of auditory cues, is without doubt a very complex one: from the sound perceived as coming from one side to the point where action is taken in the motor system to recenter the image, a great number of steps are involved in this information processing channel where the word "brain" is ultimately used as the Deus ex Machina. Recent development in neuro-anatomy and physiology of hearing have thrown some light on the peripheral coding of auditory information; nevertheless what happens to this information once it goes to higher centers is still largely unknown. From an engineering point of view, this fact does not however defeat analysis, for there are mathematical techniques to describe operationally a process without detailed knowledge of the nature of its constituents. Our intentions are now to apply one of these techniques, namely the linear system analysis, to characterize quantitatively the human operation of centring an acoustic image.

The system that we are studying can be thought of as a simple total negative feedback loop as illustrated by figure IV.7.

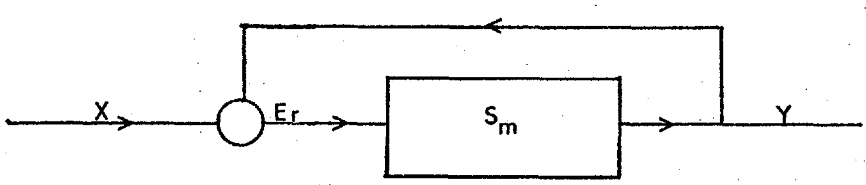

Figure IV.7 A model for dynamic binaural centring.

In this model, the input X stands for the position of the initial image presentation, the initial I.T.D., randomly selected and subsequently set by the computer; for all practical purposes, in the centring experiment reported here, this input is a step with a randomly selected amplitude.

The error signal E_r, represents the image position, also an I.T.D., as perceived by the subject; S_m symbolizes the human operation on the variable E_r, which produces an output Y such as to minimize E_r under suitable negative feedback conditions. From this description it is obvious that S_m would describe the complete human operation involved in a centring, by including both the properties of perceptual and motor reaction mechanism.

Functionally, this loop duplicates the experimental situation in the following way: in a centring experiment with zero I.A.D., the listener's task is in fact to use localization (or lateralization) clues to zero an I.T.D. by adjusting the relative time position of the auditory signals. The decision process therefore consists in using the information contained in an error signal to generate a correction to be applied, and subsequently subtracted, at the summing junction; again the result of this operation will be used to generate a new correction and converge ideally to the steady state of zero I.T.D. Provided certain stability criteria are met, this is exactly what would happen in the negative feedback system illustrated in figure IV.7 where, as previously mentioned, the loop will converge so as to minimize E_r.

The dynamic binaural judgment, in the model, E_r: the I.T.D. continuously recorded while the subject was in the process of centring the acoustic image, contains sufficient information to characterize S_m. Mathematically, S_m is defined by the relation:

$$S_m \cdot E_r = Y \qquad \text{(equation IV.1)}$$

In our experimental situation, only E_r, the I.T.D., has been recorded; however the variable X, the input, is obviously a known parameter; since, by the nature of the summing junction operation:

$$X - Y = E_r$$

it follows that:

$$S_m = \frac{X}{E_r} - 1 \qquad \text{(equation IV.2)}$$

Rigorously, these mathematical relations are valid only if S_m, E_r, X and Y are represented in the frequency domain. Consequently in order to characterise S_m, it is necessary to take the Fourier tranform of the recorded error signal and of the input signal.

This operation could easily be done on a digital computer, especially since digital Fourier transform subroutines have been made available on most computer systems. It is now understood that the notation E_r, X and Y stands for the Fourier transform of the corresponding time variable. Accordingly, S_m is the frequency response of the open-loop system.

IV.3.2 Frequency Analysis of Dynamic Binaural Centring Judgement: The Error Function.

We have shown in figure III.5 the time evolution of a centring judgement; however typical this representation is, it does not pretend to duplicate every judgement of a whole population. It has been found experimentally that there are variations in the shape and pattern of centring from one individual to another and that for a given subject, these display obvious differences from one judgement to the next. These facts stress the importance of using an appropriate signal analysis technique, in order to make any sense of the information contained in a dynamic binaural centring.

Additionally, the recording of some 800 dynamic binaural judgements, continuously sampled at the rate of 20 values per second, involve the storage of some 100,000 data values. Clearly this amount of information dictates that a form of data reduction is essential prior to the application of any sensible analysis.

In this instance, an averaging technique is appropriate since, from both points of view, it offers the advantages of reducing the amount of data while it attenuates the effect of individual differences present in successive recordings of the same signal. In the usual way, an average response is computed in aligning below each other the time dependent variable and, using the time of stimulus presentation as a synchronization reference, adding the various contributions columnwise. In general, this operation however presupposes identical stimulus presentation, which is not the case here since our input stimulus is a random variable.

Consequently the averaging technique cannot be used in this manner. Alternatively, one could normalize the responses, previous to averaging, dividing by the value of their individual input stimulus: this method however has a disadvantage in that it over-emphasizes the importance of noisy responses generated from low-level stimuli and, for our purposes, was found impractical.

We have chosen a different method of averaging. In a manner not dissimilar to what we have reported earlier, the binaural centrings were grouped in one of four classes according to their initial I.T.D., and subsequently averaged in each group. Because this averaging process is selective in terms of input signal amplitude, this technique offers some advantages over the previous ones: if the system's error signal is input amplitude dependent, to a certain extent this property will not be lost in the averaging process. Indeed it is feasible that the listener would not use the same strategy to position a nearly mid-line image as opposed to recenter a "far left" one, for example. Accordingly, the forthcoming analysis will be performed for each independently averaged group and consequently should be illuminative about the degree of non-linearity that an input-dependent human behaviour could produce.

Figure IV.8 shows the dynamic centring judgements, averaged in the four classes as previously described; five subjects were used and a total of approximately 150 dynamic centrings are represented in each group.

In these curves, contrary to the impression given by figure III.5, the average dynamic centrings would develop from an apparently very stable centring mechanism, since only a small amount of oscillation is in evidence. A possible explanation for this point is that the oscillatory behaviour like that shown in figure III.5

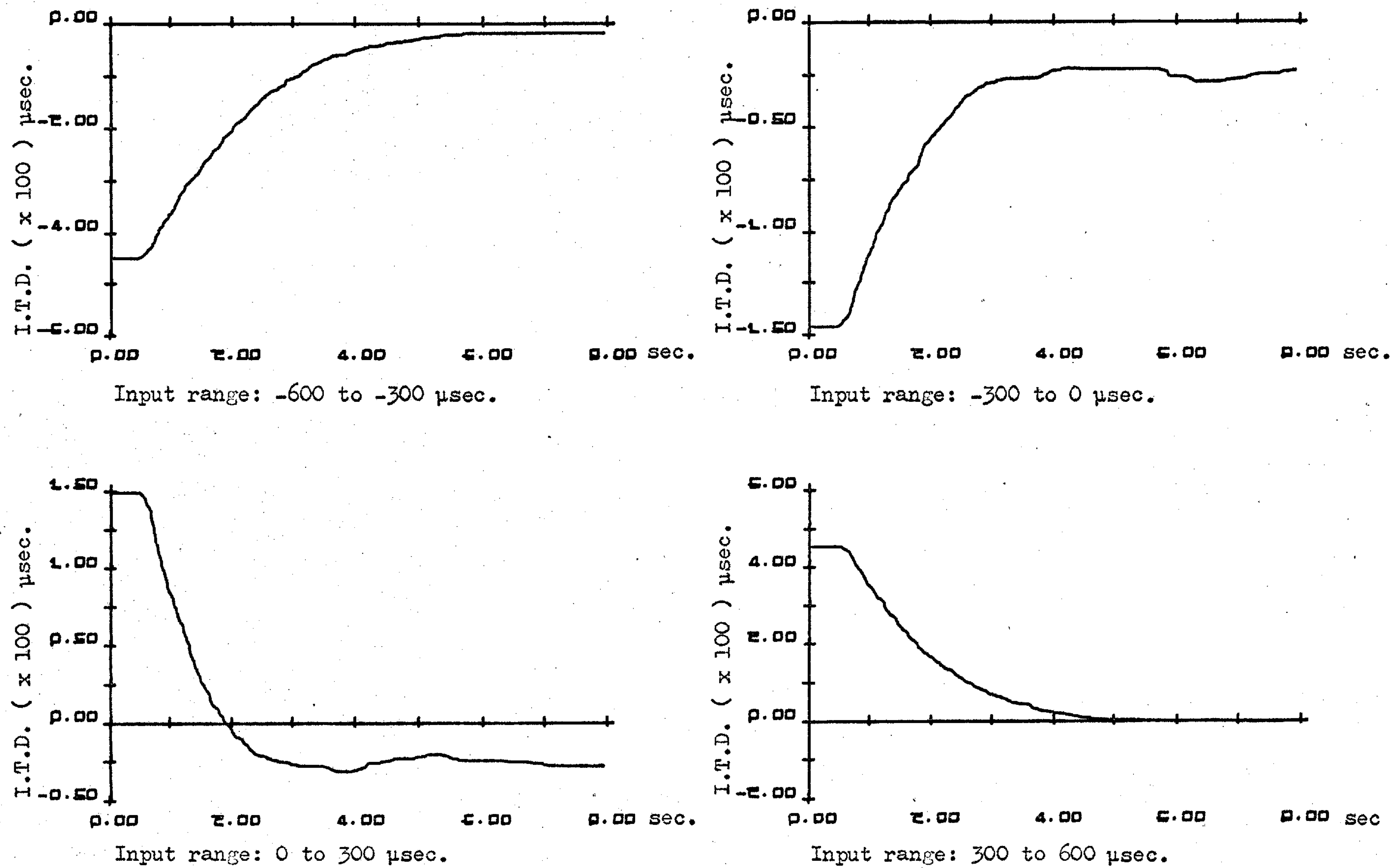

Figure IV.8. Averaged dynamic centring judgements. Each group averages 150 centrings.

would not be common to every binaural judgement, and occuring at various frequency and phase for various subjects the oscillations would tend to cancel out. Presumably this also implies that such definitely marked oscillations are not an essential feature of binaural centring.

A useful way of performing a frequency analysis of this signal, is to look at it as if it was the output of a system (S_{er}), and, knowing the input, find the frequency response of this system.

The frequency response of a system is in fact the Fourier transform of the impulse response of this system. In the particular system, S_{er}, that we are dealing with, the impulse response has not been measured: the various averages of figure IV.8 represent rather four responses to averaged step inputs. Since we consider the system linear, the impulse response can be calculated by taking the time derivative of the step response; in this case a subsequent Fourier transform of these derivatives will provide the function of S_{er} for four different levels of input signal.

Figure IV.9 (a and b) shows the results of such a mathematical operation on each of the four "impulse responses"; here, each of the various functions has been plotted as a Bode diagram, a familiar representation in linear system analysis. It is observed that the error function performs an operation on the input, similar to a high pass filter, with an asymptotic low-frequency attenuation of 20 db per decade and a slight (3 db) resonance above .15 Hz.: this resonance is probably what is left, after the averaging process, of the various oscillations to which we referred earlier.

The phase characterisitics of these functions also duplicate the behaviour of a high-pass filter by displaying a phase lead below the cut-off frequency, and a negligible phase shift above this frequency.

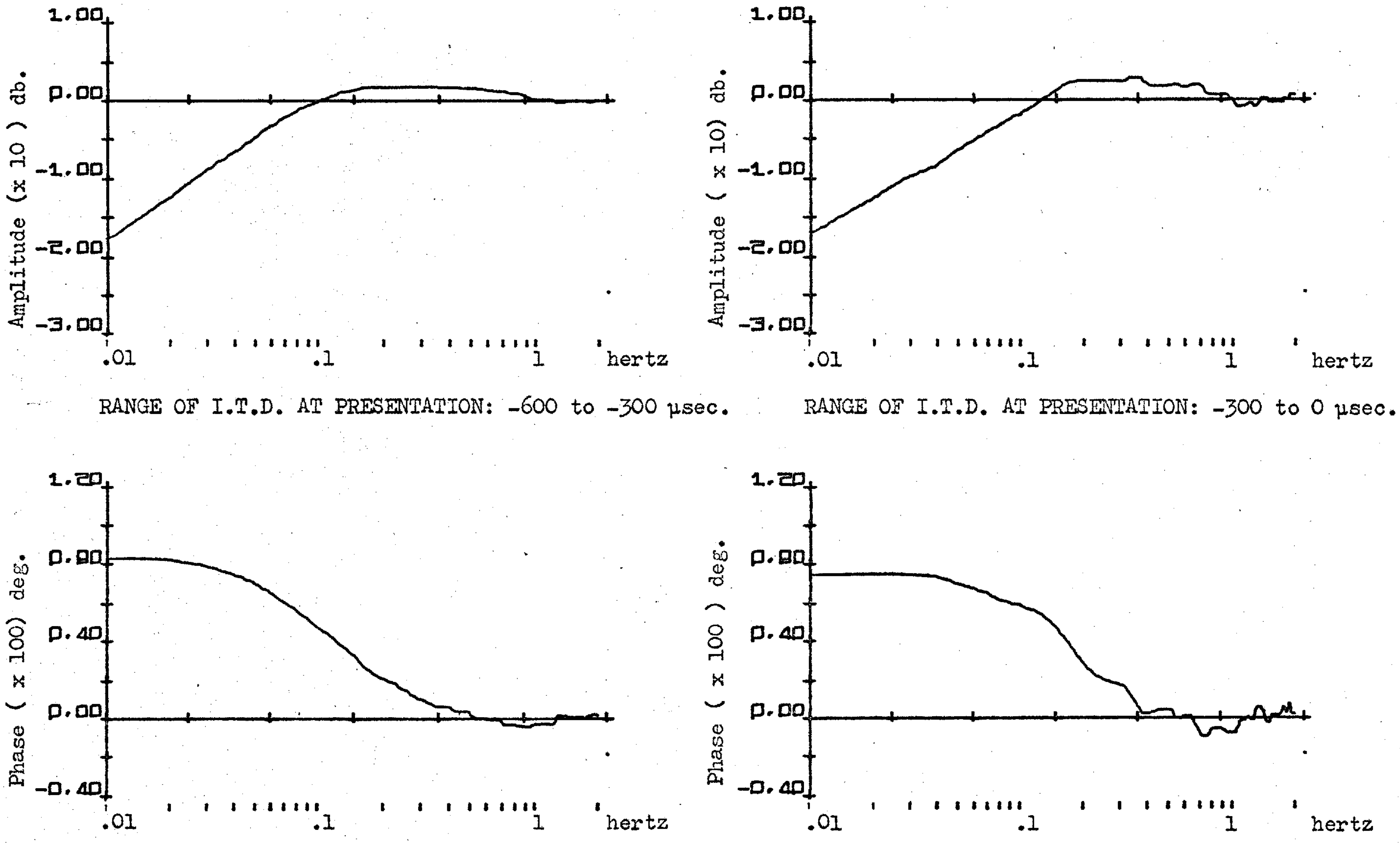

Figure IV.9 a. Frequency spectra of the error function,as derived from averaged step responses.

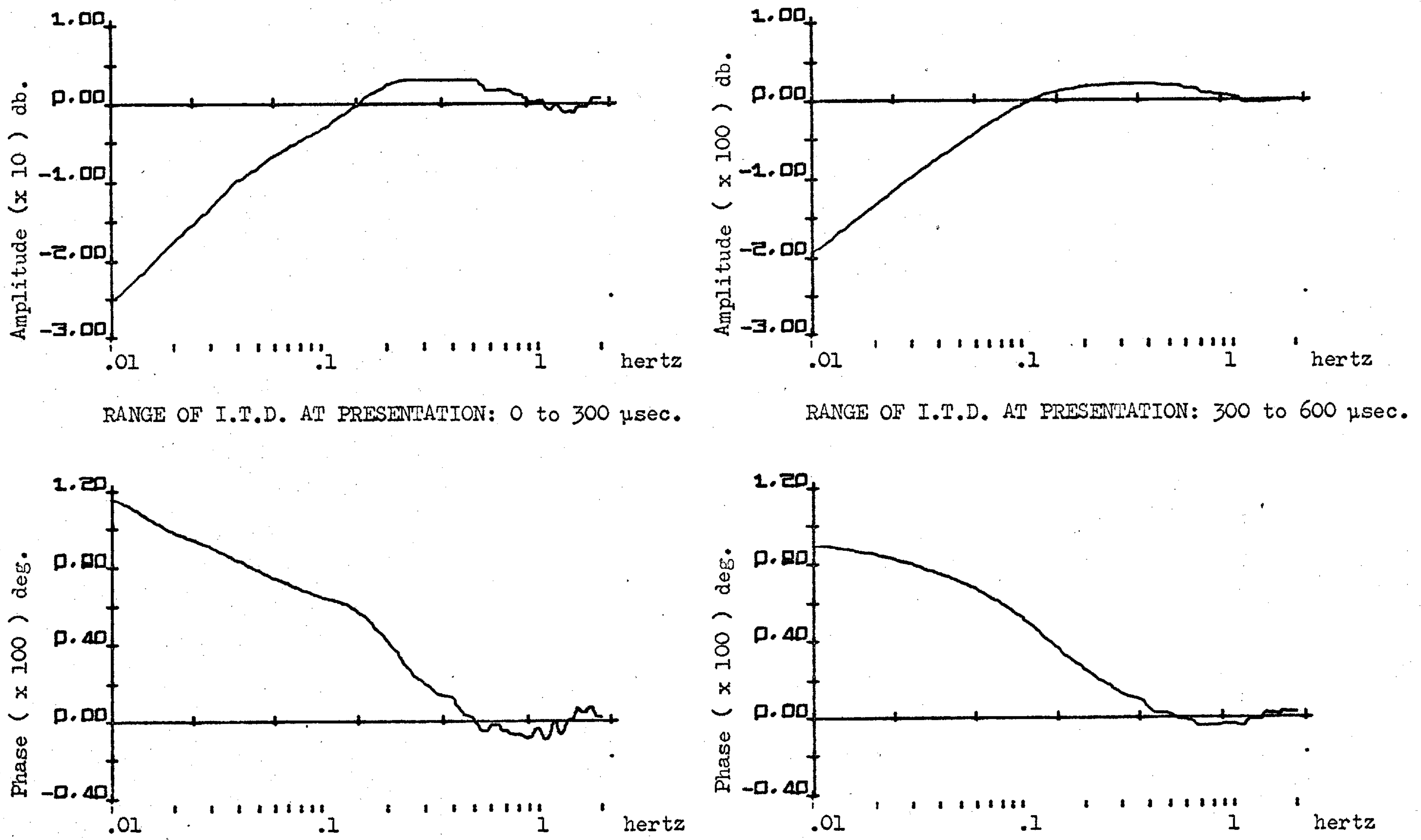

Figure IV.9 b. Frequency spectra of the error function,as derived from averaged step responses.

At the low frequency range, the system behaves like a differentiator from the amplitude and the phase point of view (the phase leads by 90^{o}). In short this system could be reasonably well approximated by a first-order high pass filter of the form:

$$H(s) = s/(s+a) \qquad \text{(equation IV.3)}$$

where H(s) is in the frequency domain the frequency response of the system, and "a" is the cut-off frequency of the filter.

Graphically, the cut-off frequency of S_{er} is found to be in the range of .08 hz, for the 3 db point; in other words if the present analysis is correct, the task of tracking manually a moving auditory source would, practically, start to fail at frequency above .08 hz, a point where the error would equal .707 times the input signal amplitude.

A last observation to be made relates to the fact that the four curves that represent the error function for four different input levels look very similar to each other. Again this could serve to indicate that the system under study is not amplitude dependent, and therefore is in accordance with one of the premises of linear system analysis.

In conclusion, the frequency analysis of the error function, as presented here, has evidenced a mechanism equivalent to a high-pass filter operation, which is quite certainly common to every error function in any system involving a human operator: the higher is the input frequency, the greater is the error, up to the point where the magnitude of the error nearly equals the magnitude of the input, in which case any further human reaction is useless. However, for the first time in the field of study of manual tracking of auditory moving sound source, this error function has been quantified and put in a form from which the error could be predicted for a general class of input signals.

IV.3.3 Open Loop Characteristic of the Auditory Tracking Mechanism.

The error function described in the previous section, can now be used in equation IV.2 to determine the frequency response of S_m. The mathematical operation consists simply in performing a complex division and subtraction, using E_r and X.

Figure IV.10 shows the four S_m obtained from the error defined earlier; the results are presented on a Bode diagram.

The amplitude characteristic curves, almost a straight line in every case, indicates that we are dealing with a system performing like an integrator; the phase characteristic showing a 90^o lag at the low frequency end, equally supports this view. However an increasing phase lag towards the high frequencies, suggests that an element of pure delay is present in the system. Indeed at 1.8 hz, the phase has shifted by 360^o: the delay involved therefore equals .6 sec.

From these observations, the system S_m could then be approximated by a relation of the form

$$G(s) = \frac{B}{s} \cdot e^{sT} \qquad \text{(equation IV.4)}$$

where, obviously, T = .6 sec; B is found graphically as the point where $|G(s)| = 0$ db, and is therefore in the range .48 to .6 rad/sec.

Ostensibly, the various frequency responses presented here are not very different one from the other; it could therefore be concluded that S_m is, within limits, amplitude independent.

The question arises now as what does an open-loop transfer function, describing a human operation, correspond to? The answer is

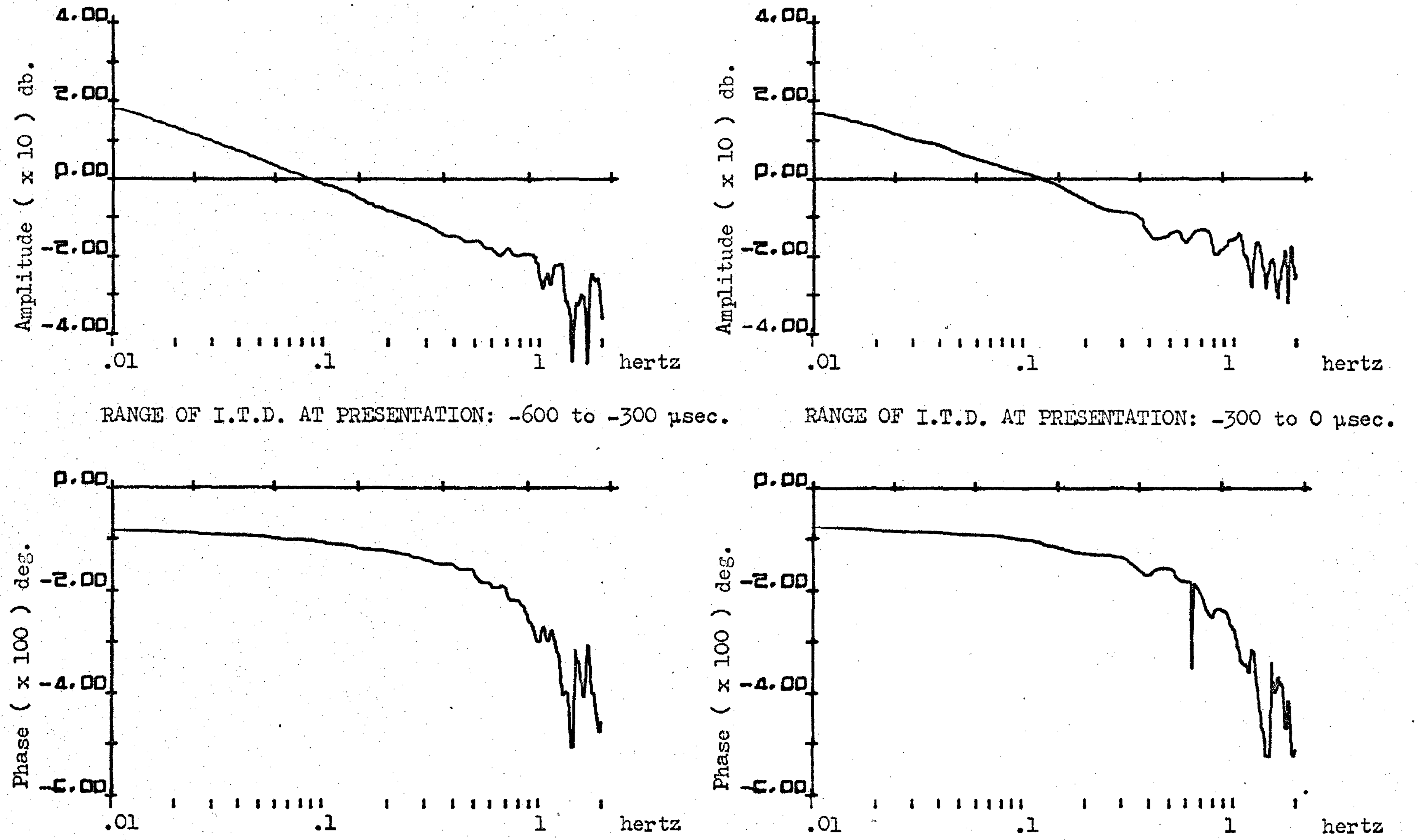

Figure IV.10 a. Open loop frequency responses of the system S_m.

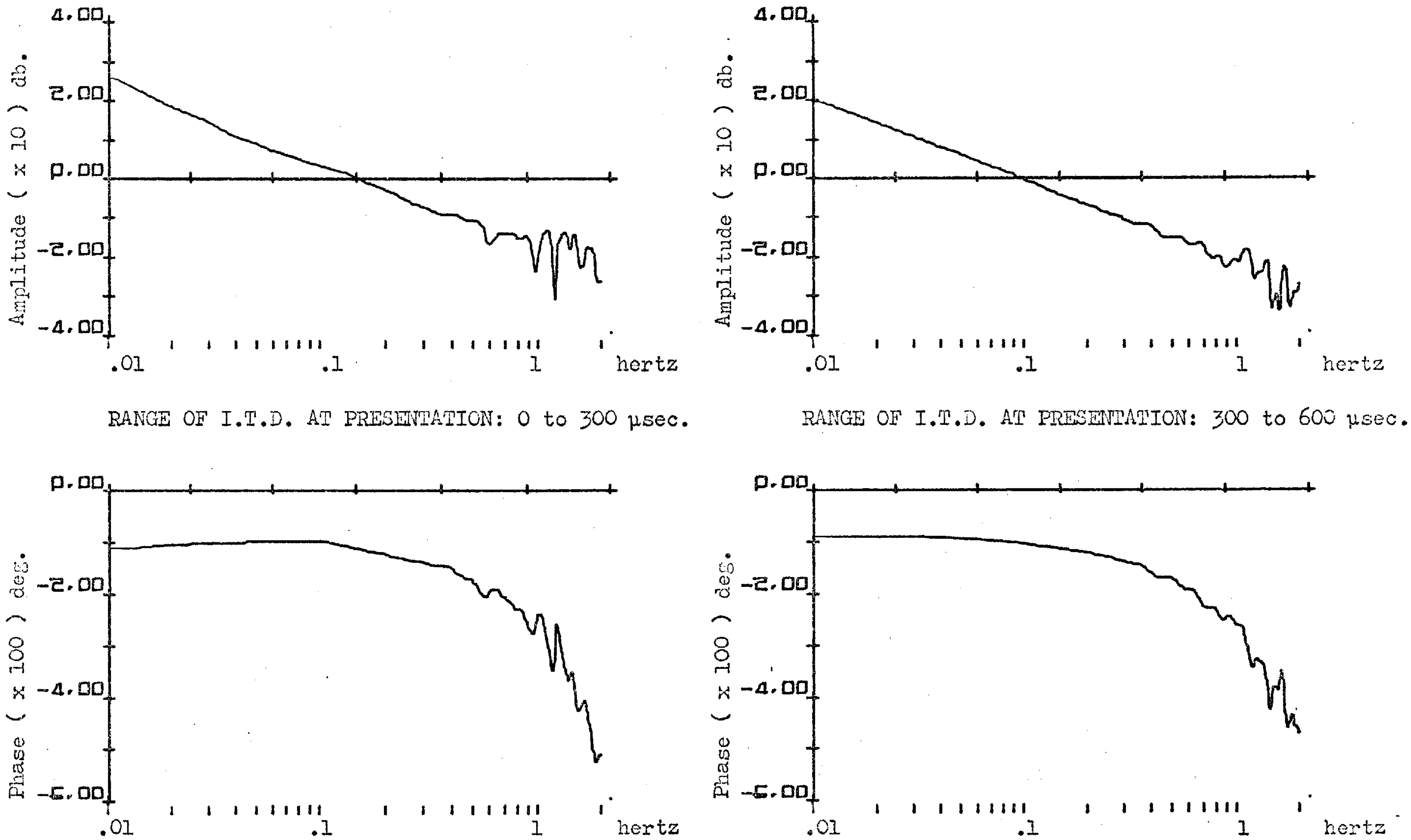

Figure IV.10 b. Open loop frequency responses of the system S_m.

that it corresponds to the situation where the control turned by the subject to recenter the image, is inoperative. As it is, this fact would normally qualify the analysis presented here as a typical academic interest of the most useless kind. However, in the context of a linear system approach, a definition of S_m has broader application and is more interesting: ideally, it would enable one to predict the human behaviour in auditory tracking, under any linear (and some times non-linear) feedback conditions for which, for instance, stability criteria can be applied. This indeed opens to a very general class of problem, where binaural information is an essential feature of a human operation.

IV.3.4 The Listener as a Human Operator.

The knowledge of the error function can also lead to a definition of the frequency response of S_m under closed-loop condition: a complex subtraction of the error function from the transform of the input, does in this case supply the desired answer, previously labelled "Y".

In a way, this function, (Y), corresponding to the correction to be applied, describes the frequency response of the listener considered as a human operator. Obviously this response represents the human operation specific to the case of binaural centring reported here and consequently is not directly applicable to other types of feedback configuration as, for that matter, S_m is.

Figure IV.11 (a and b) shows the four functions obtained from the set of open-loop frequency responses. As expected, these responses are analogous to a low-pass filter operation of a first

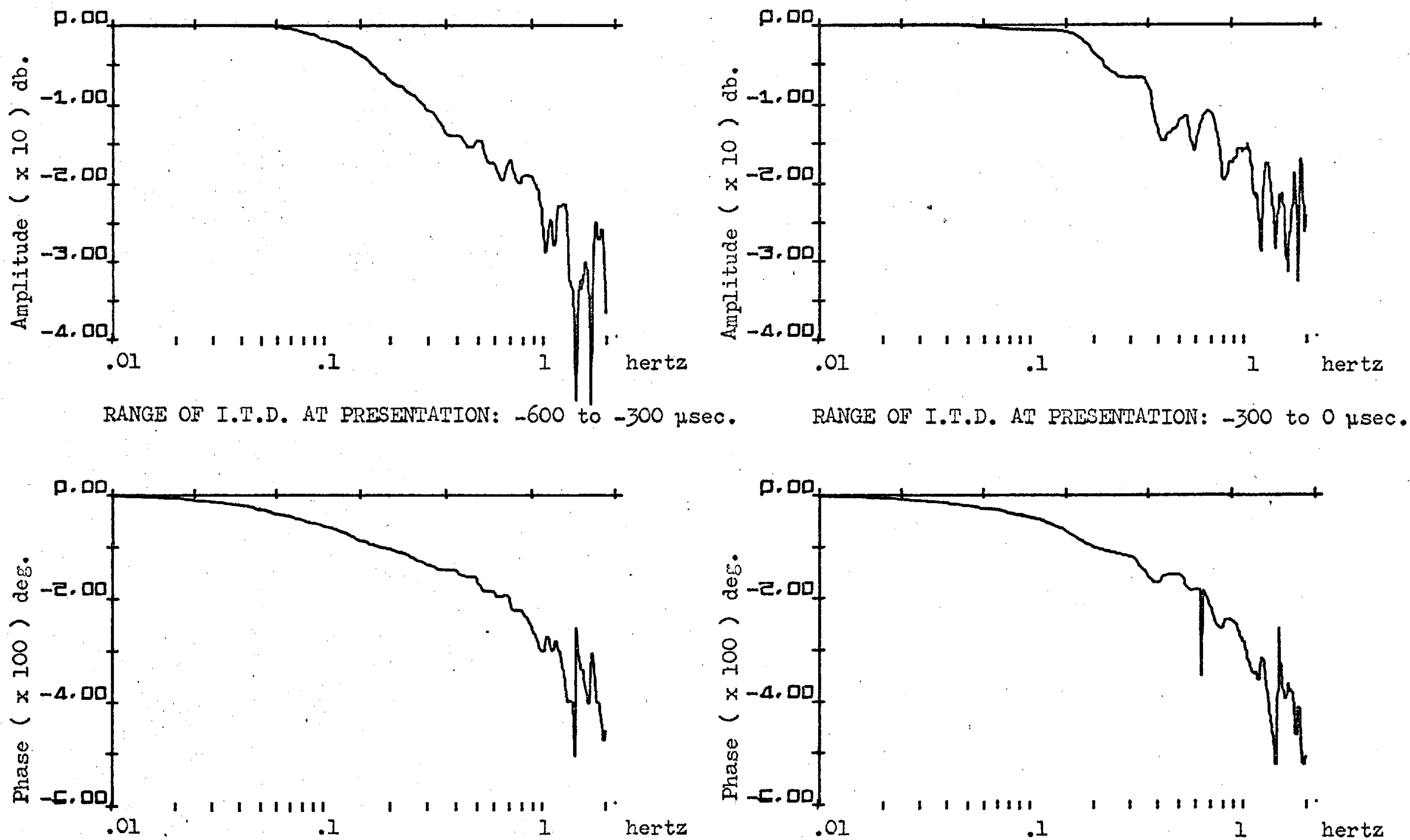

Figure IV.11 a. Frequency responses of a human operator in an auditory tracking task.

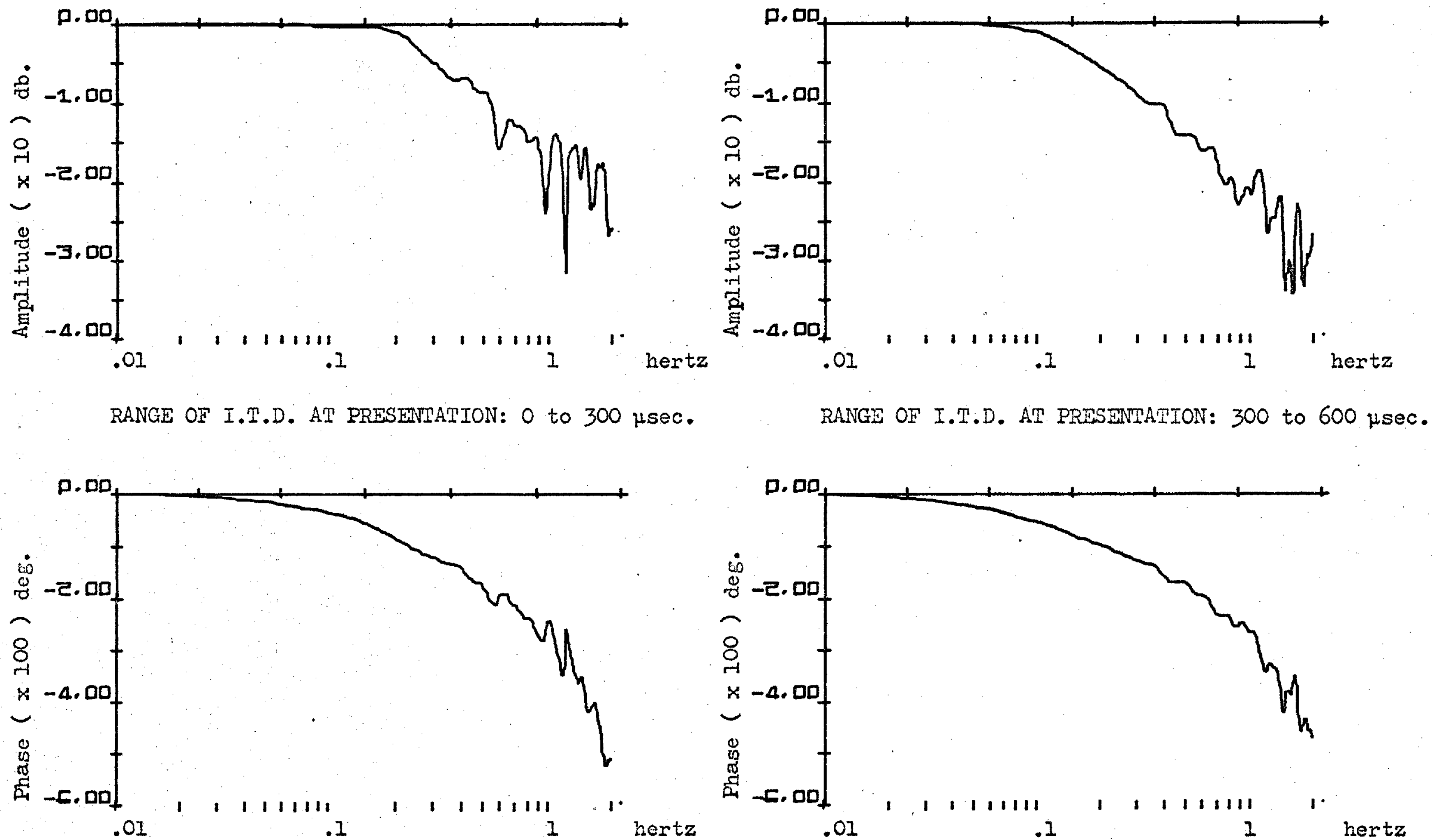

Figure IV.11 b. Frequency responses of a human operator in an auditory tracking task.

order system; here again, the introduction of an element of pure delay of .6 seconds is necessary to account for a phase shift of 450^{o} at 1.8 htz: a first order low pass filter, would display a phase lag of only 90^{o} at the high frequency end of the frequency response curve. The various frequency responses, broadly similar to each other, suggest that this particular human operator system has a cut-off frequency in the range .15 to .2 hz.

These findings remain to be verified in experiments dealing specifically with the auditory tracking, if it is not only for the fact that the cut-off frequency of the system is surprisingly low compared to other human tracking systems. The visual system, for instance, has been shown to display a tracking frequency response cutting-off nearly a decade higher, i.e. 2 to 3 hz (Milsum, 1968). However there is no evidence in the results presented here, to suggest that the auditory tracking of predictive waveform, say sinusoid, would not lead to the same conclusions as the one we have come to in this chapter.

CHAPTER V

INTERACTION OF SIMPLE AUDITORY TRANSIENTS WITH INTER-AURAL AMPLITUDE DIFFERENCE

V.1 Introduction

The psycho-acoustic effects introduced by an inter-aural amplitude difference (I.A.D.) have for a long time been the subject of extensive experimental studies involved with the problem of binaural fusion. Basically the phenomenon can be described as follows. In the event that binaural fusion is achieved, i.e. a sound is perceived binaurally as having some spatial attribute, the introduction of an additional I.A.D. on the acoustic waveform will alter the spatial character of that sound: it will be perceived as if the sound source had moved towards the ear getting the louder signal. To a certain extent this effect is similar to the one produced by introducing an I.T.D. which also can alter the spatial character of a sound by moving its perceived position towards the side of the leading signal. In these circumstances it becomes feasible to evaluate the effect of an I.A.D. on binaural fusion in terms of an equivalent I.T.D.: hence the measure commonly used to quantitatively describe this effect, called the I.T.D./I.A.D. trading ratio.

Several methods have been used to evaluate this parameter. Direct recordings of cell activity (figure III.4) in the accessory superior olivary nucleus (Hall, 1964) have evidenced a time/intensity neural coding at this level of the auditory pathway; a trading ratio for the accessory olivary units could be determined by adjusting the relative time and intensity to give equal probability of firing; the ratio was found to vary from 10 µsec/db to 90 µsec/db according to the average intensity of the input signals.

Psycho-physically, several attempts have been made to measure this ratio, reported with values spreading in the range of 1 µsec/db to 100 µsec/db. Examples: Shaxby (1932) (quoted by David, (1959)) reports a trading ratio obtained psycho-physically with binaural correlated transients of 1 µsec/db, while David et al. (1959) using a centring technique with transients, reported values as high as 100 µsec/db. (see figure III.4). More recently, using similar methods, again with binaural transients, Sayers and Lynn (1968) reported an I.A.D./I.T.D. trading ratio in the range of 10-35 µsec/db; as far as the variation of this ratio with respect to the average sound intensity is concerned, they came to conclusions totally opposed to what has been found earlier psycho-physically and physiologically: "Our results do seem to suggest that the ratio is approximately constant in the normal hearing environment, at least for signals of the type that give rise to a fused binaural image of a predominantly low pitched impulsive character". (Sayers and Lynn, 1968).

There are numerous examples and experimental evidences of this sort to illustrate that psycho-physical measurements of the trading ratio have shown a very high degree of variability, sometimes leading to conflicting conclusions for which, as expected, there are many theories. (Whitworth and Jeffress (1962), Hafter and Jeffress (1968), Sayers and Toole (1964b)).

For that matter, the most interesting ones are the latest theories that relate the I.A.D./I.T.D. effect to the peripheral transformation and subsequent coding of the acoustic signals. Lynn and Sayers (1970) have proposed a model in which the binaural fusion is achieved in the cross-comparison of the post-stimulus neural activity emanating from corresponding cochlear loci. Although they are not specific about the mechanism that would achieve this comparison physiologically, they nevertheless propose that the centre of gravity of the P.S.T. histogram (figure II.8) could be the significant parameter in this particular instance: this proposition is not totally unjustified since the estimated shift of the centre of gravity lies in the range of 37 µsec/db, a value frequently reported in psycho -physical measurements.

From a perceptual point of view, this proposition implies that the binaural image is of a complex kind, made up of several images that would arise from the cross-comparison between the individual peaks of the right and left ear P.S.T. histogram; in this instance various types of behavioural I.A.D./I.T.D. effects could be measured according to the way this complex image is subjectively analysed or perceived. (Monro, 1971).

As discussed earlier, a trading ratio of say 37 µsec/db could be expected in the situation where an "averaged" complex image is reported. A smaller trading ratio, 10 µsec/db, or less, would on the other hand originate from the cross-comparison of individual peaks. This has been investigated by Monro in a simulation of the auditory transduction process; combined effects of neural sensitivity and refractoriness gave rise to a change in latency in the individual peaks, in the range of 10 µsec/db, and therefore would account for the reported small values of trading ratio. Finally as far as the large values of ratios are concerned, this situation would arise when an individual image is reported as a result of a cross-comparison say of the first peak of the left P.S.T. histogram versus the second peak of the right P.S.T. histogram.

By its simplicity, the proposition put forward by Monro,(1971), Sayers and Lynn,(1968), is very attractive. However it is believed that there is a lack of experimental evidences to support it. Monro himself, commenting the I.A.D. experiments reported by Sayers and Lynn mentioned that:

> "The distribution of individual judgments is not indicated and as before such information would be helpful as the hypothesis that the separate images are not in fact substantially shifted by I.A.D. could be tested further. One would expect to see some judgments affected by I.A.D. in which an average is performed by the listener and others less influenced by I.A.D. in which separate images are identified".[†]

The present chapter will be devoted to this question, mainly aiming at studying the problem related to the high degree of variability in the reported measurement of the I.T.D./I.A.D. trading ratio: for that matter our experimental technique is ideally suited since it enables us to collect the large number of data necessary to build up the "distribution of the individual judgment".

We will also report studies on the time evolution of binaural judgments, treating the set of judgments recorded at one sitting as a sequence of events. We will demonstrate that the sequences display some adaptive behaviour in the perceptual mechanism, which in turn could account, in part, for the variability in the values of the reported trading ratios.

[†]Monro, D.M., 1971, The implications of peripheral auditory mechanisms for the perception and recognition of speech and other acoustic waveform. PhD Thesis, University of London, p.197.

V.2 Experimental Study on the Effect of a 10 db. I.A.D. on Binaural Centrings

V.2.1 The Distribution of Centring Judgments

A series of experiments was conducted with the subjects introduced in the preceding chapter. Using our automated technique, the subjects were asked to recenter an acoustic image randomly presented with I.T.D.* ranging from -600 μsec to +600 μsec. Apart from a nominal 10 db I.A.D. (the right ear getting the louder signal), the experiment was otherwise identical to the ones reported in the previous chapter; this was ensured by the fact that the same control program was used to generate the experiment. The clicks, (repetition rate 20 per sec.) were low pass filtered at 2.0 kc, and 128 judgments were recorded for each subject, in one sitting.

Figure V.1 (a and b) shows the judgment distribution obtained in this manner; figure V.2 (a) shows the distribution of the whole set of judgments (768). For comparison purposes, the histogram obtained from the previous experiments without I.A.D. has been replotted in figure V.2 (b).

Some important observations can be reported here although these results need to be compared to other experimental evidence to be properly interpreted; a more elaborate discussion on this question follows in a later section of this chapter.

For the moment the facts are that the individual distributions as well as the group histogram, are definitely unimodal; as previously argued this would indicate that there is no multiple image reported in this experimental condition.

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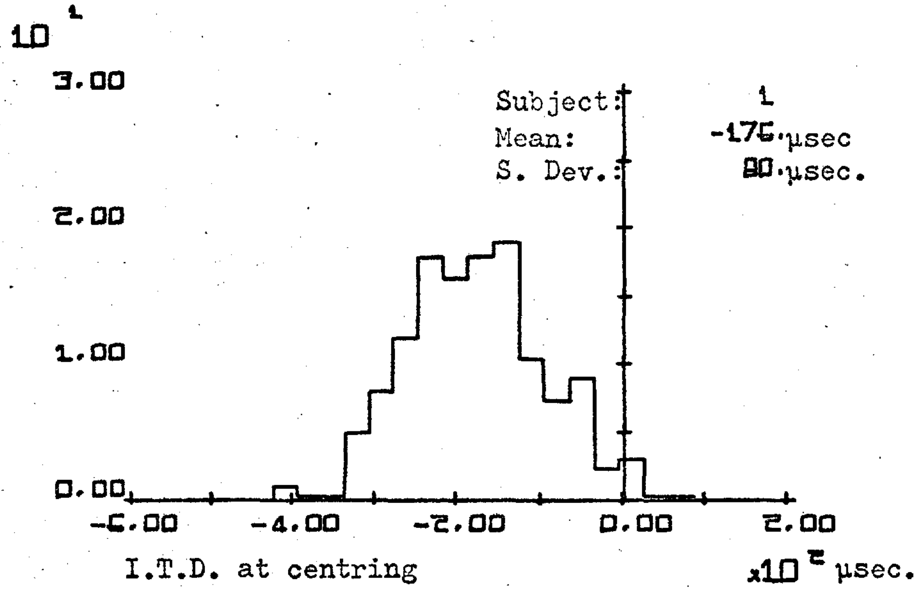
* In this chapter the I.T.D. reference is taken relative to the loudest pulse.



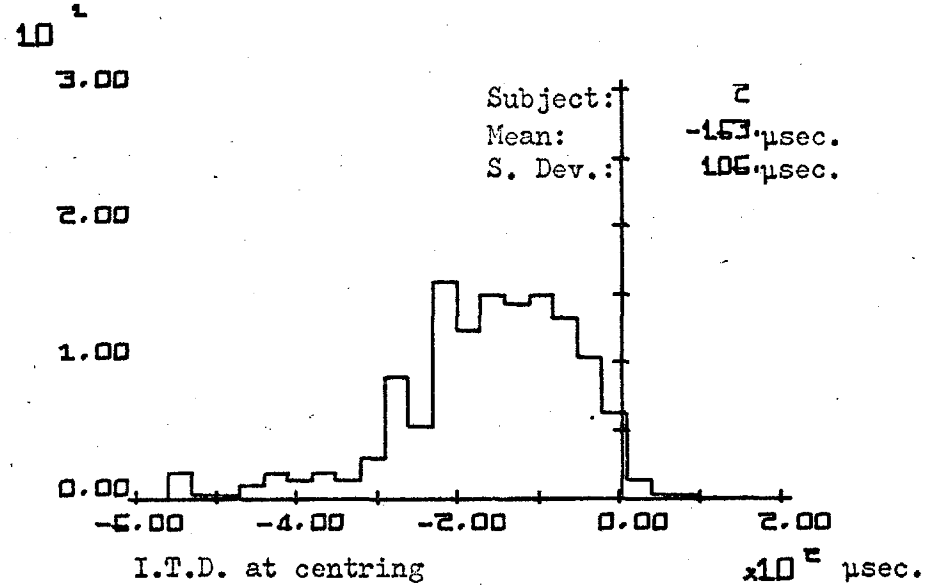
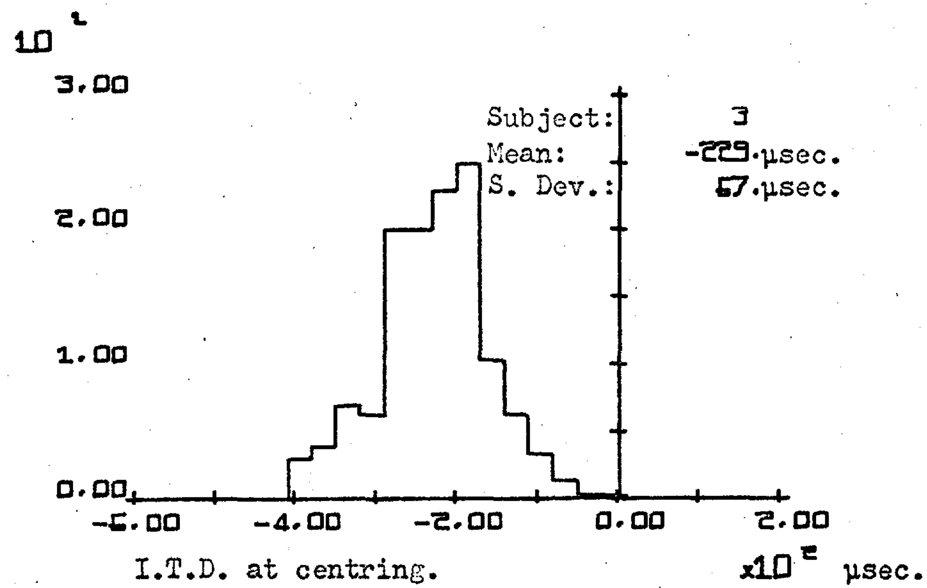
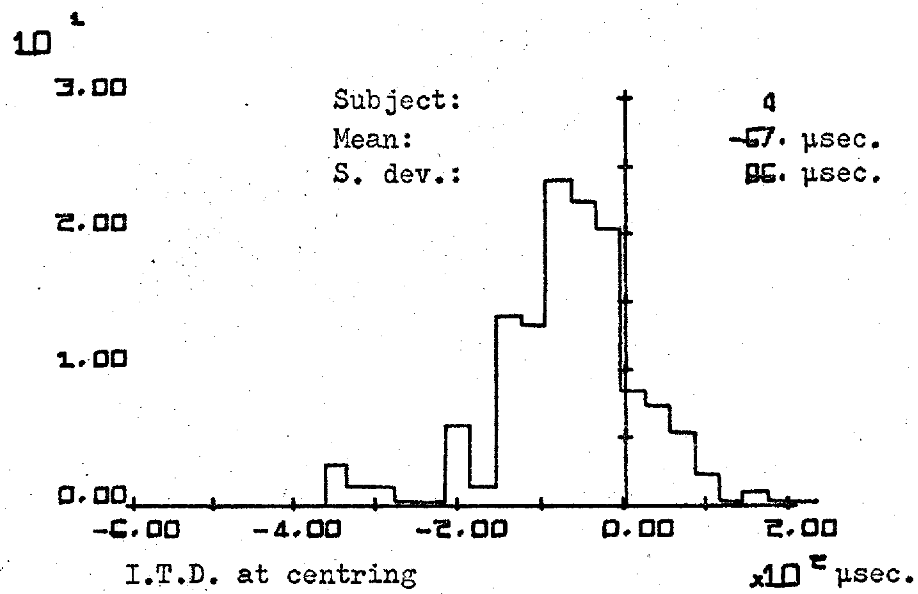


Figure V.1 a. Binaural judgement histograms.
Single clicks with I.A.D. 10 db.





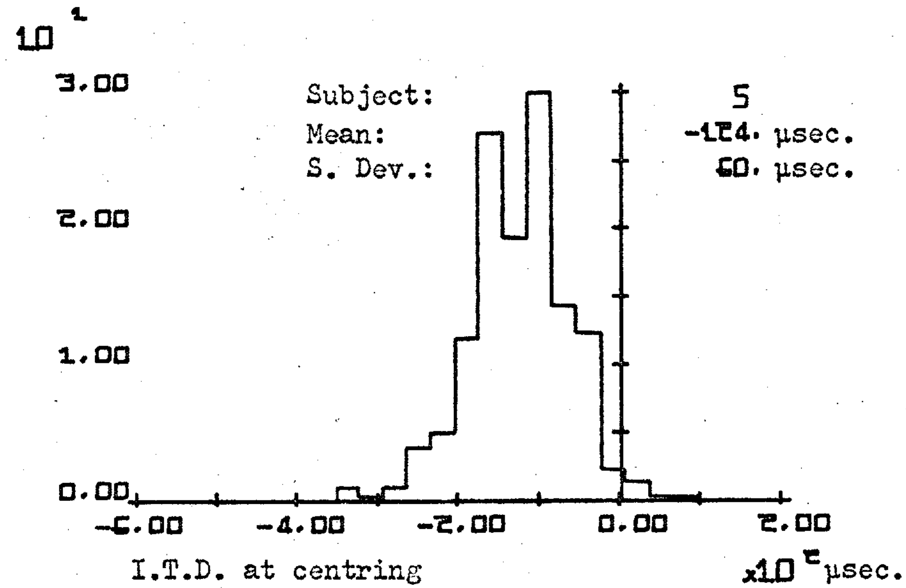
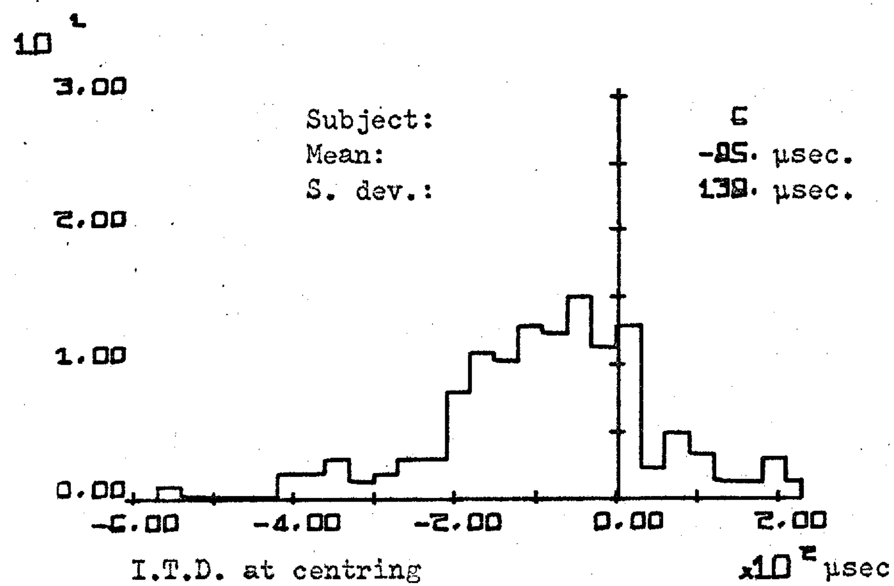


Figure V.1 b. Binaural judgement histograms.
Single clicks with I.A.D. 10 db.



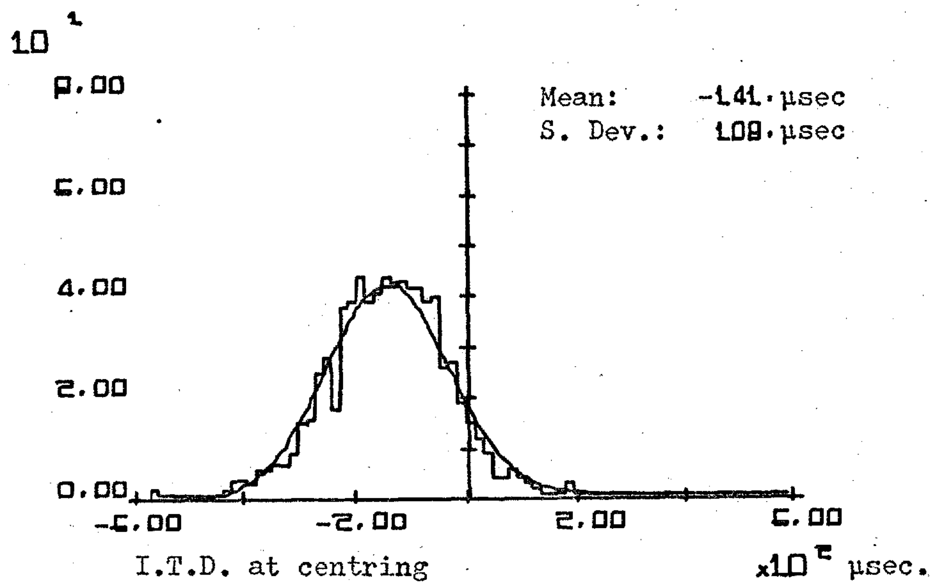


Figure V.2 a. Binaural judgement histogram obtained by combining the distributions of Figure V.1 (a and b). Single clicks, I.A.D. 10 db.

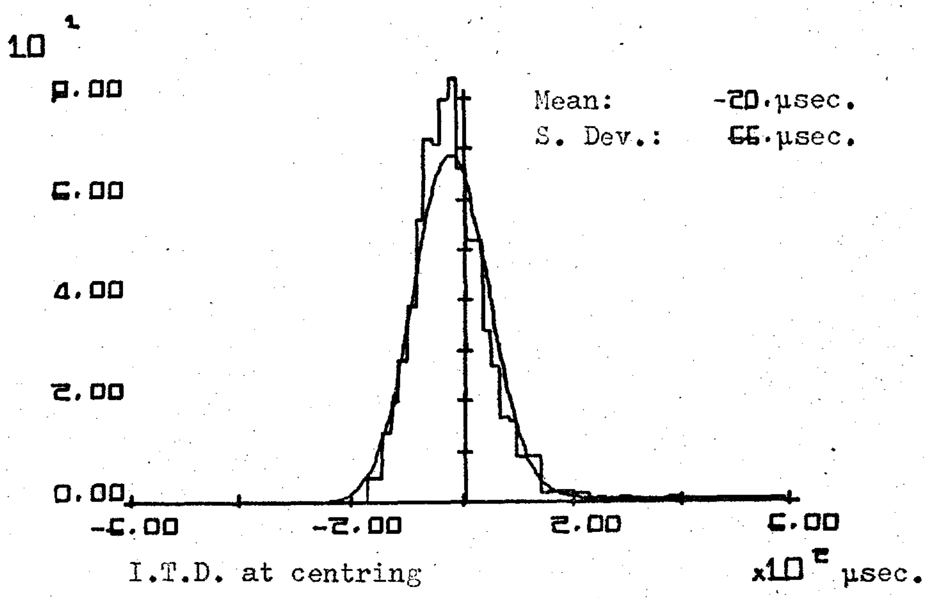


Figure V.2 b. Binaural judgement distribution redrawn from figure IV.2. Single clicks, I.A.D. 0 db.

The trading ratio, determined here by the shift of the mean of the distribution is estimated at 14 µsec/db for the group under study; for the individual histograms this ratio is found to vary from 7 µsec/db (subject no.4) to 23 µsec/db (subject no.3). We are therefore able to report as previous workers, a large degree of variability in the evaluation of this ratio.

A point previously reported by Harris, (1960), relates to the standard deviation of the distribution; compared to the histogram of centring of simple transients without I.A.D., the deviation of the group distribution is nearly twice as large.

In part this is due to the grouping of different distributions with widely different means; but it is also due to the individual distributions, themselves having a larger standard deviation than in the case of centring without I.A.D. (compare with figure IV.1), by a factor of 1.5 (subject no.4) up to 1.8 (subject no.6).

There is no readily available explanation for the fact that a process containing more "noise" than in the equal level case, underlies the binaural centring of acoustic signal with I.A.D. An interesting way of investigating this particular matter is to look at the evolution of the trading ratio in the course of the experiment; this is done by taking the set of judgments reported by a given subject and treating this as a set of successive events on which signal analysis technique can be subsequently applied. The next section reports results obtained in using this method.

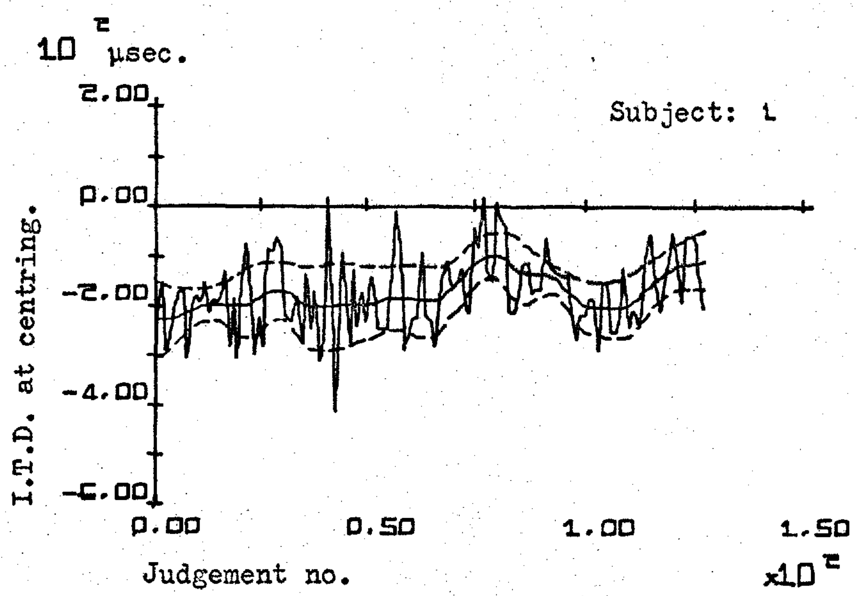
V.2.2 The Binaural Judgment Sequence

Figure V.3 (a and b) shows the six binaural judgment sequences, coming from the same set of data that generated the distribution of figure V.1. The vertical axis gives the time interval between the clicks at the time of centring; the horizontal axis, is the binaural judgment number. Successive centring judgments have been joined by linear segments to form a continuous curve.

A digital filtered version of this signal, (see section III.6) is also shown to evidence the general trend. Additionally a form of demodulation of the sequence is presented as an upper and lower limit (dashed trace) of the mean. This demodulation was obtained by filtering the sequence that constitutes the absolute difference between the filtered signal and the original signal. The demodulated waveform is indicative, in this case, of the instantaneous "noise" present in the signal, since it gives a form of running average of the deviation from the mean.

The sequences presented in this form indicate that the binaural judgment process undergoes some modification in the course of the experiment. This is particularly obvious with subject no.2, 5 and especially 4: with the latter, the mean judgment is seen to shift from -275 μsec down to nearly -30 μsec. In other words, the trend suggests that the subjects would adapt to an inter-aural amplitude difference by progressively not being influenced by its effects.

There is an abundant literature on psycho-physical studies of adaptive phenomena, but in general, these report experiments that could not be compared on the same ground as those we present here: subjects were for instance exposed to highly adaptable stimuli.



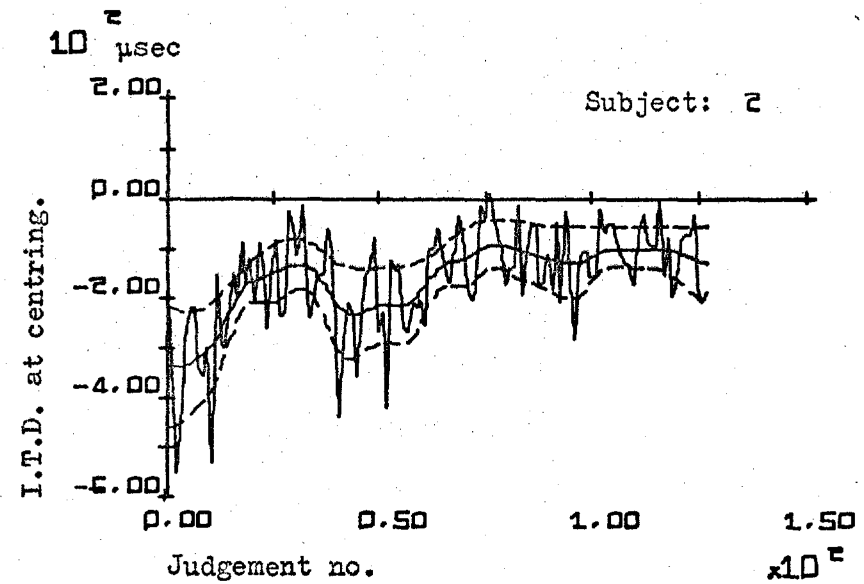
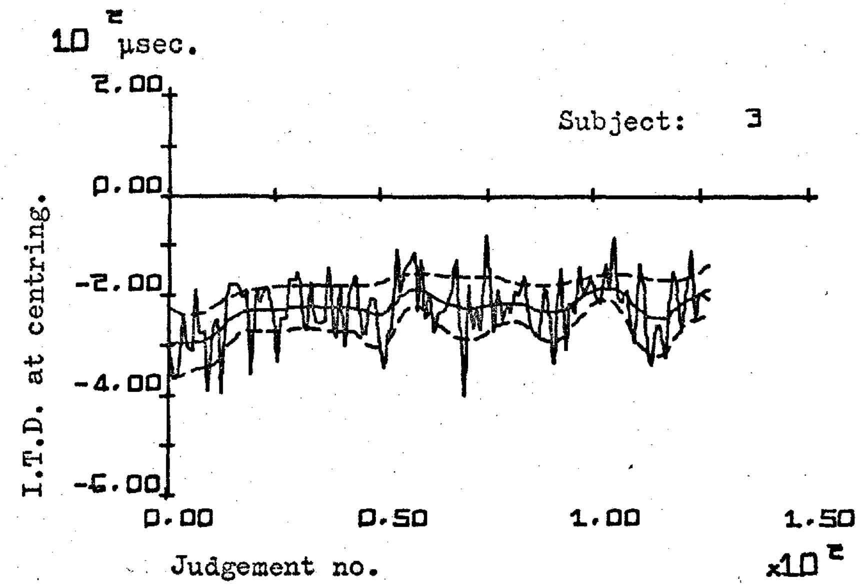
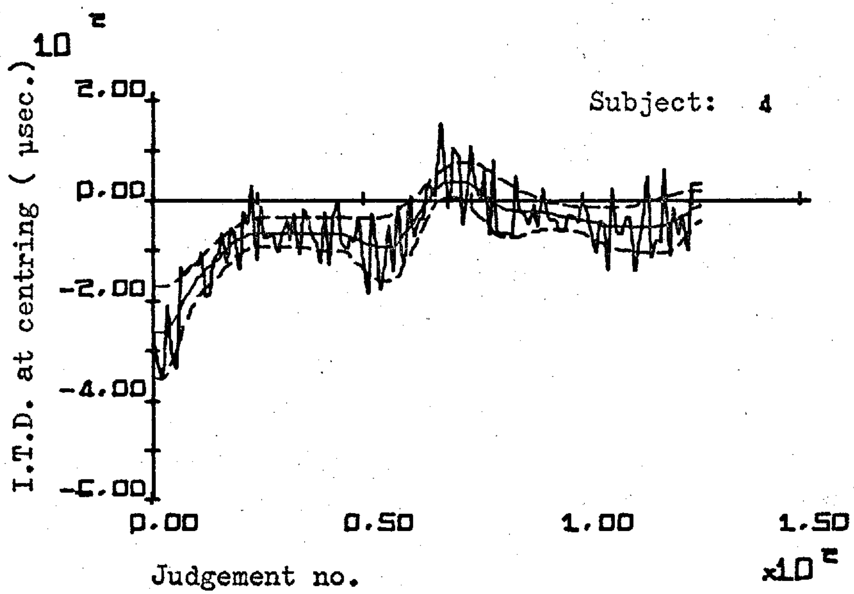


Figure V.3 a. Sequences of binaural centrings.
Single clicks, 10 db I.A.D.





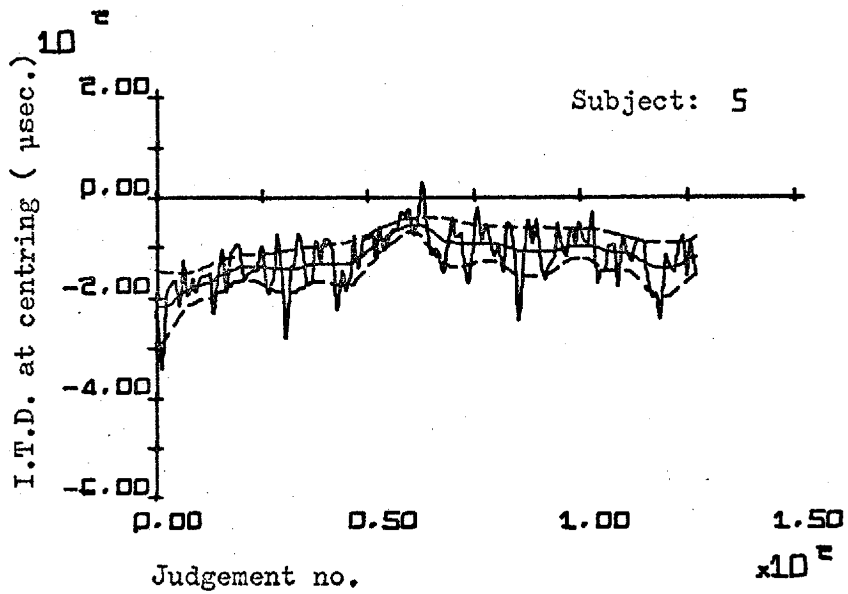
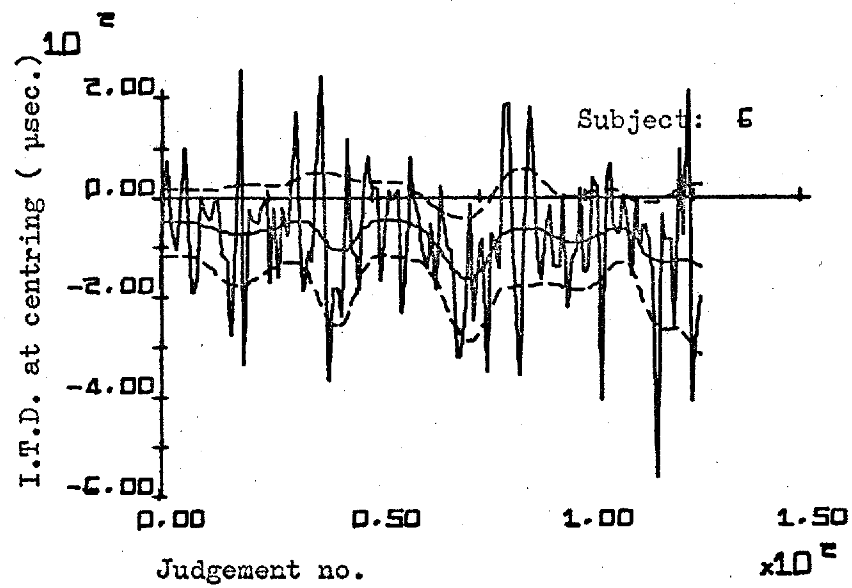


Figure V.3 b. Sequences of binaural centrings.
Single clicks, 10 db. I.A.D.



(Cf. Bekesy, (1960), using 95 db SL, 800 hz tones). We want to point out that auditory adaptation can be traced even in what is thought to be a much less adaptable type of stimulus such as the one used in our binaural centring experiments, and that it can significantly alter the judging behaviour of certain subjects.

For that matter, psycho-physical measurements of the trading ratio, using a centring technique, can be seriously affected by adaptation: subject no.4 for example, would report a trading ratio of 27 µsec/db at the beginning of the experiment, (averaging say the first 5 judgments) and a ratio of 7 µsec/db later (averaging judgments no.25 to 30). In part this could account for the wide range of trading ratio reported by previous workers, and certainly is worth paying further attention. The next section will report more experiments, performed with a greater number of subjects, mainly to ensure that the phenomenon is not an artifact of the population under study.

V.3 Further Study on Adaptation to Inter-Aural Amplitude Difference

V.3.1 The Time Course of Adaptation in Binaural Experiments.

Through headphones, the subjects were presented rarefaction clicks having an I.A.D. of 10 decibels (right ear 75 db, left ear 65 db nominal peak sound level with reference to .0002 dynes/cm^2, repetition rate 20 per sec.). The subjects were asked to adjust the I.T.D. to position centrally the binaural image, at which time the I.T.D. was recorded. In one sitting, the subjects were given 32 binaural presentations, with a 4 seconds resting period between each judgment. A total of 31 experiments were performed with 20 subjects (14 naives, 6 experienced).

The sequences of binaural judgments were then averaged to give the results shown in figure V.4a. The abscissa represents the judgments number in the sequence, with the ordinate as the averaged I.T.D. that would compensate for a 10 db difference. Again, a digital filtered version of the curve is plotted to show the general trend.

The results indicate adaptation, that largely stabilizes within about 10 binaural judgments. The time to make a judgment was also averaged for the population under study, and results are plotted versus judgment number in figure V.4b. The adapting curve can now be replotted against time (taking into account the 4 seconds resting period between each judgment) as in figure V.4c, where an adapting time constant of some 85 seconds can be found.

These experiments indicate that in the case where a large population is used, the repetitive evaluation of the trading ratio using binaural centring technique, leads to time-dependent results.

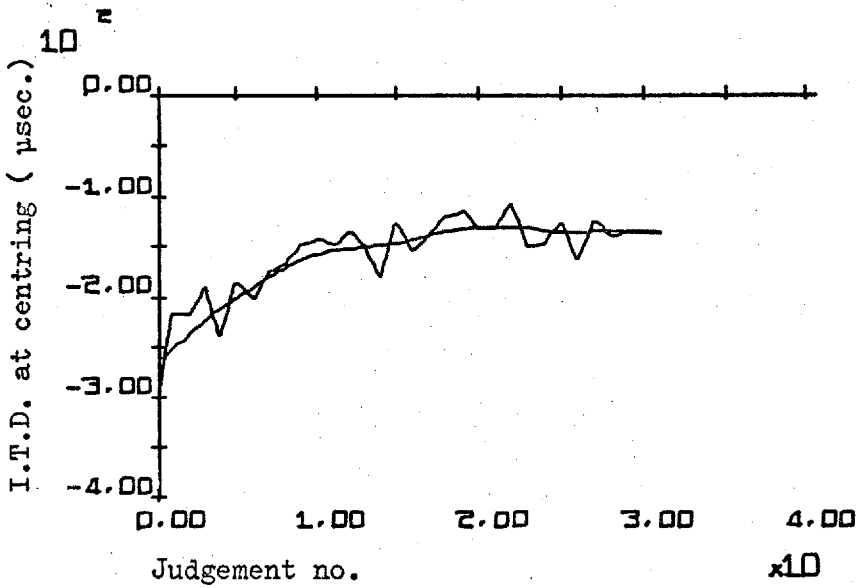


Figure V.4 a.

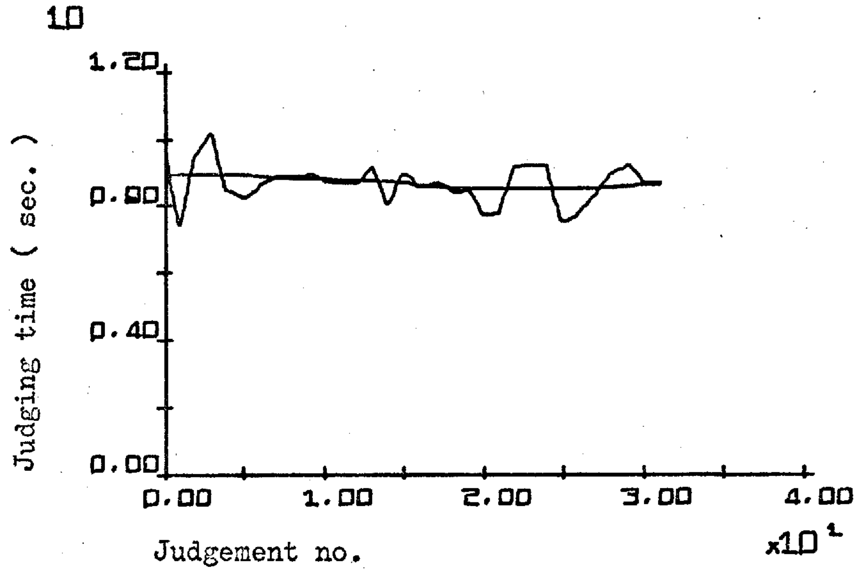


Figure V.4 b.

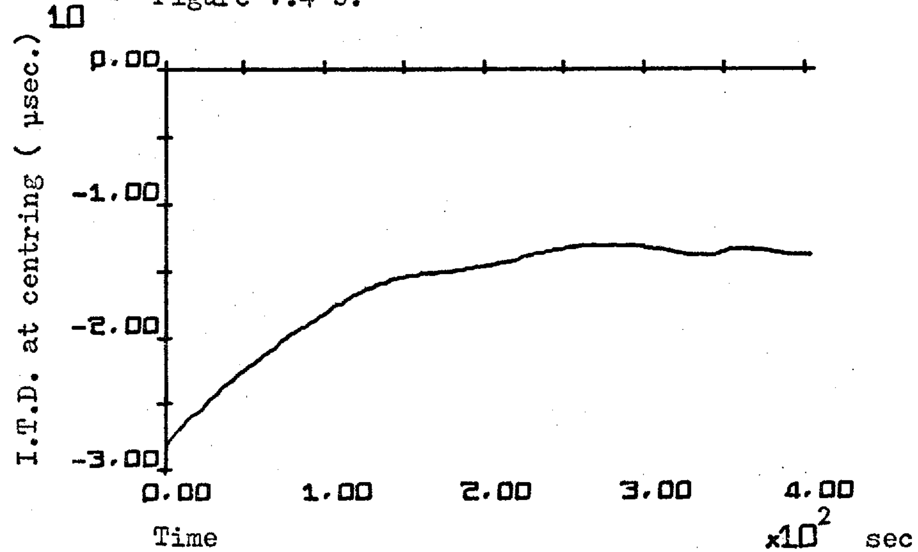


Figure V.4 c.

Figure V.4

a) Averaged binaural judgement sequence. Single clicks, I.A.D. 10 db.

b) Averaged judging time sequence. Single clicks, I.A.D. 10 db.

c) Adaptation curve of binaural centring of single clicks with 10 db. I.A.D.

Since this result has been obtained with a substantial group of subjects it must be concluded that this effect would have arisen in experiments reported by previous workers (often using one or two subjects), and thus would definitely have contributed to confusion when measurements of the trading ratio were made. It must be emphasized that adaptation does alter significantly the judgment process even when very few judgments (typically 3 to 8) are considered in sequence, and therefore is bound to have happened in many experiments. It is important to note however that the effect is not obvious in every judgment sequence (see for example subject no.1 in figure V.3) and consequently appear to be mainly significant when a population average is considered.

V.3.2 The Time Dependence of Binaural Judgment Distributions.

The model put forward by Monro,(1971) to account for some I.A.D. effects in binaural fusion, associates the larger values of the trading ratio with the centring of secondary images. In this context, one could interpret the adaptive effect shown earlier, as a progressive shift of attention from one image to another: the order of magnitude of the trading ratio at the beginning and at the end of the experiment that we just reported, respectively 27 µsec/db and 13 µsec/db, would be in accordance with this view.

The distribution of adapted binaural judgments should give some insight on this point. Figure V.5 (a to c) shows four distributions obtained from the set of 31 experiments mentioned in section V.3.1; figure V.5a gives the histograms built by taking the first five judgments in each of the 31 sequences; figure V.5b to

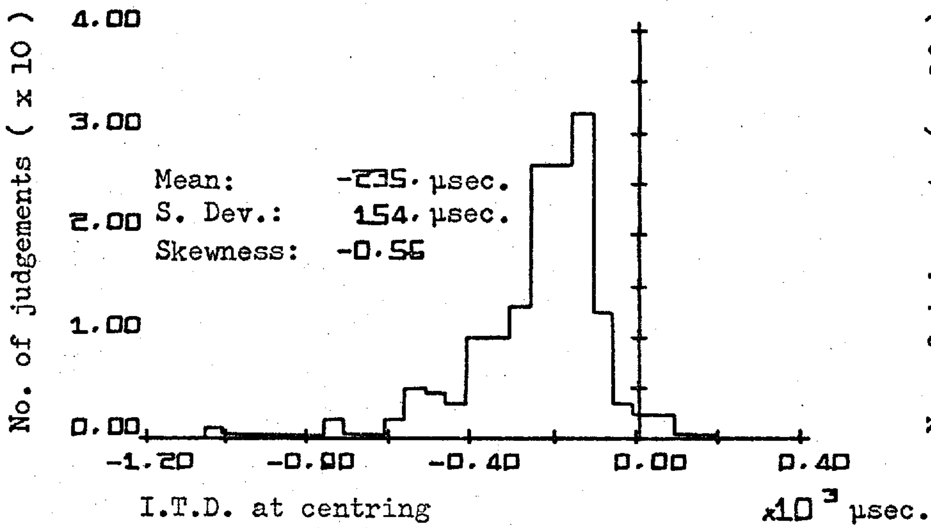


Figure V.5 a.

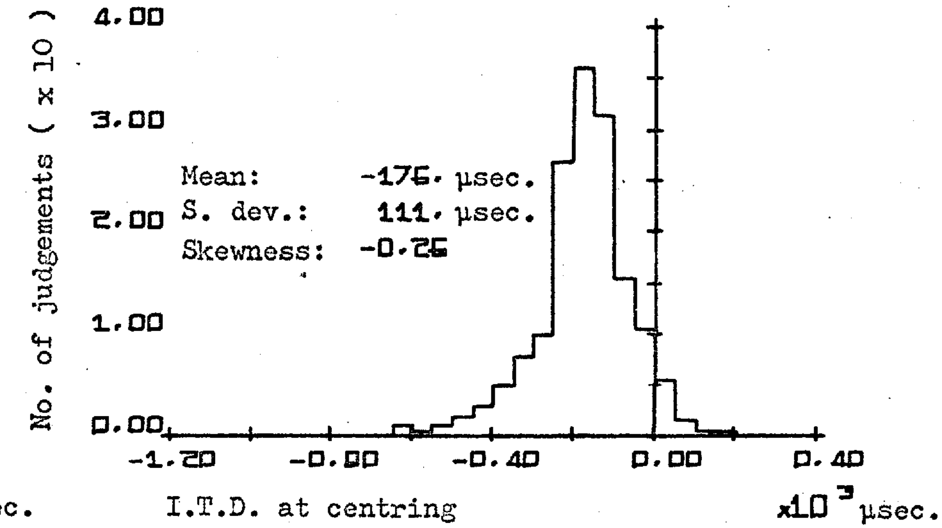


Figure V.5 b.

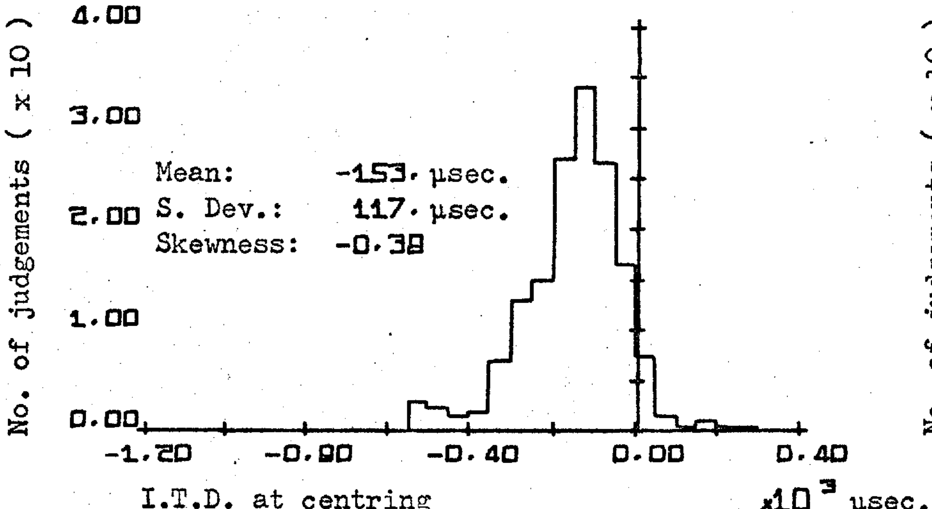


Figure V.5 c.

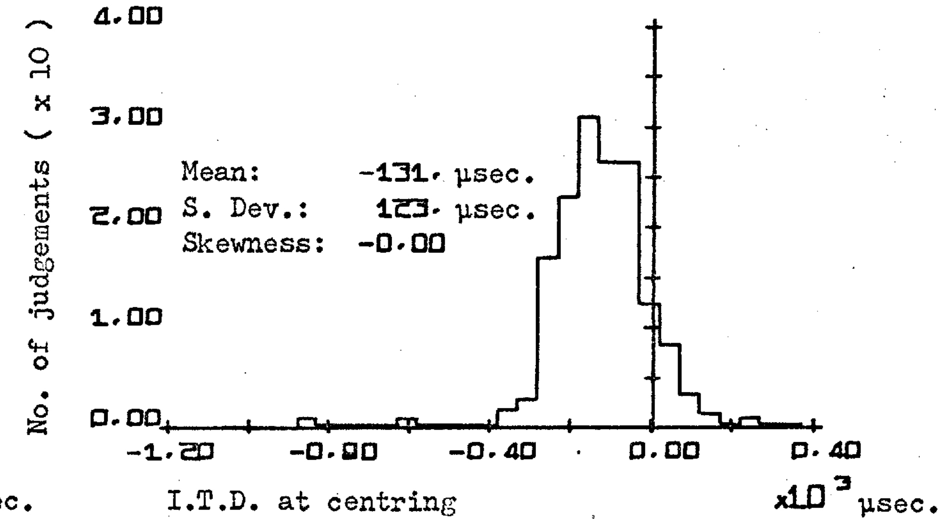


Figure V.5 d.

Figure V.5 Distributions of successive groups of binaural centrings. See text for details.

V.5d shows the respective distribution of judgments no.6 to 10, 11 to 15 and 16 to 20.

These distributions confirm the trend suggested in the previous analysis of the judgment sequence: the mean progressively shifting from -235 to -131 µsec, suggests an underlying adaptive process; a test of difference of means between distribution V.5a and V.5d demonstrated that the difference was highly significant (.01 level).

Some new interesting features now appear in these distributions: the behaviour of the standard deviation and the skewness, both decreasing in value in the course of the experiments, suggest that the adaptation process does not simply produce a progressive shift in the center of gravity of the histogram, but that it also alters the distribution itself.

This fact would be consistent with the view of "multiple images" proposed by Monro; looking at these distributions, it is possible to infer that attention is being paid to an image in the region of -400 to -800 µsec, continuously shifting to another image in the region of -150 µsec. The resolution of the histogram does not enable a clear demonstration of this point, but it certainly suggests that the theory proposed by Monro, (that several images coexist) combined with the dynamic effect that we have found (i.e.. shifting of the mode itself), does present a plausible explanation of the type of adaptive phenomenon that has been evidenced. A more elaborate discussion on these points will be presented in a later part of this chapter.

V.3.3 The Effects of Acoustically Unbalanced Inputs.

The adaptation effects that we have been describing, are presumably due to a prolonged exposure to repeated acoustic stimuli. The effects, probably present in most binaural experiments, do not cause any particular problem when the stimuli are of the same intensity at the site of each ear: in this case both ears adapt to the same level and the subsequent binaural fusion remains broadly unaltered.

However, in binaural experiments with I.A.D, the degree of adaptation would be different for each ear. There are several matters to confirm this view. Figure V.6, for example, shows auditory fatigue to be related to the amplitude of the input signal: it follows therefore that in the case of prolonged exposure of acoustic stimuli, inter-aural amplitude difference will be associated with an inter-aural adaptation difference.

It has been found in the previous section, that the "prolonged" exposure to which we are referring, need last only 85 seconds, typically 8 to 10 judgments, to significantly alter the pattern of binaural fusion. This poses a serious problem to binaural experimentation, particularly in the case where it is necessary to obtain a large number of judgments in one sitting, in order to eliminate day to day variation, for instance.

The technique that we have adopted to overcome this difficulty is essentially based on the assumption that binaural adaptation occurs because of a prolonged exposure to an unbalanced acoustic input. In fact, it consists simply in inverting the acoustic input at every binaural judgment (the right headphone input becoming the left one, and vice versa), so that the long term average of the sound intensity is the same for each ear.

Using a modified version of the control program to produce alternately inverted I.A.D.** we have carried out a set of experiments with the six trained subjects referred earlier (these subjects were also mentioned in chapter II, in the Bekesy audiometric tests).

An experiment consisted of 128 random presentations (in one sitting) of acoustic transients, low-pass filtered at 2 khz and with a 10 db I.A.D. alternated with transients of -10 db I.A.D. at successive presentation. In the original sequence, the first, third, fifth... judgments, related to the +10 db presentations while the second, fourth,... corresponded to the -10 db presentations.

The six sequences of 64 odd numbered judgments (+10 db I.A.D.) were averaged to give the results of figure V.7, where a filtered sequence is also shown. It is seen that, in accordance with the previous assumptions, no adaptation remains when the inverting technique is used: the average binaural judgment stays at a relatively constant level. It is also interesting to note that the average centring judgment, occuring at around -300 μsec, satisfactorily duplicates the value (-270 μsec) found at the beginning of the binaurally adapted judgment sequence, (figure V.4), where presumably no significant adaptation had occurred.

The corresponding distribution of judgments is shown in figure V.8. The center of gravity of the histogram relates to a trading ratio of 30 μsec/db, i.e. nearly twice the ratio of adapted judgments.

** Our convention is that +10 db I.A.D. implies that the right ear gets the louder signal; -10 db I.A.D. indicates that the left ear gets the louder signal.

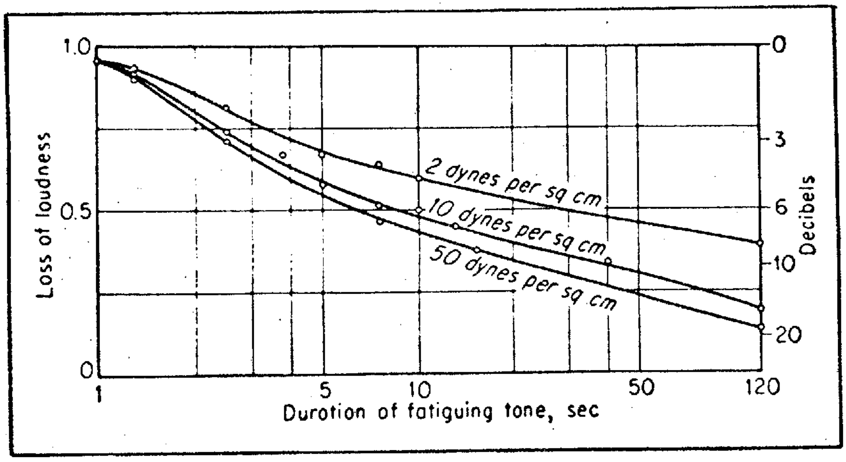


Figure V.6. Fatigue as a function of the intensity of the fatiguing tone. The tone was 800 hz at three intensities as indicated. From Bekesy (1960) p. 357.

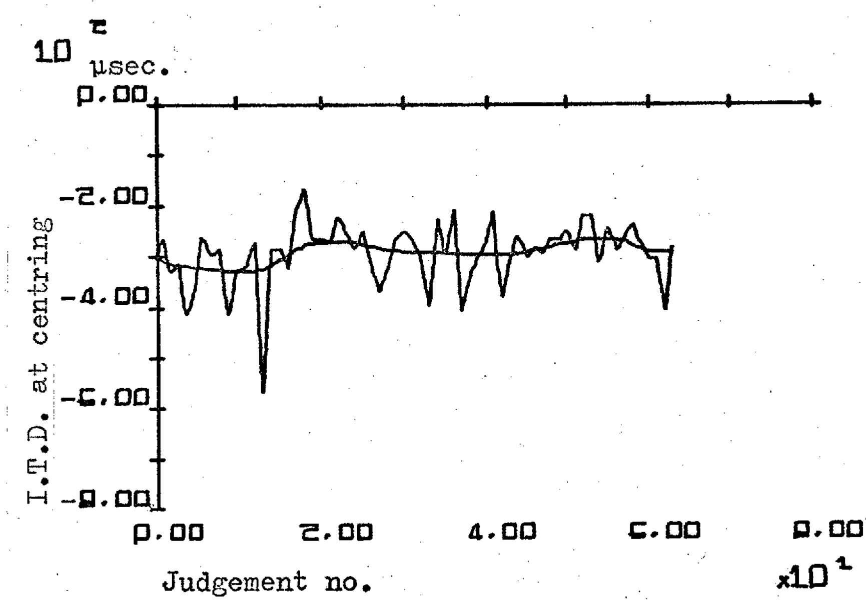


Figure V.7 Averaged binaural judgement sequence corresponding to the + 10 db. presentations. The experiment was conducted in a way such as the mean sound intensity was the same for each ear on a long term basis. 6 subjects averaged. No adaptation effects remains.

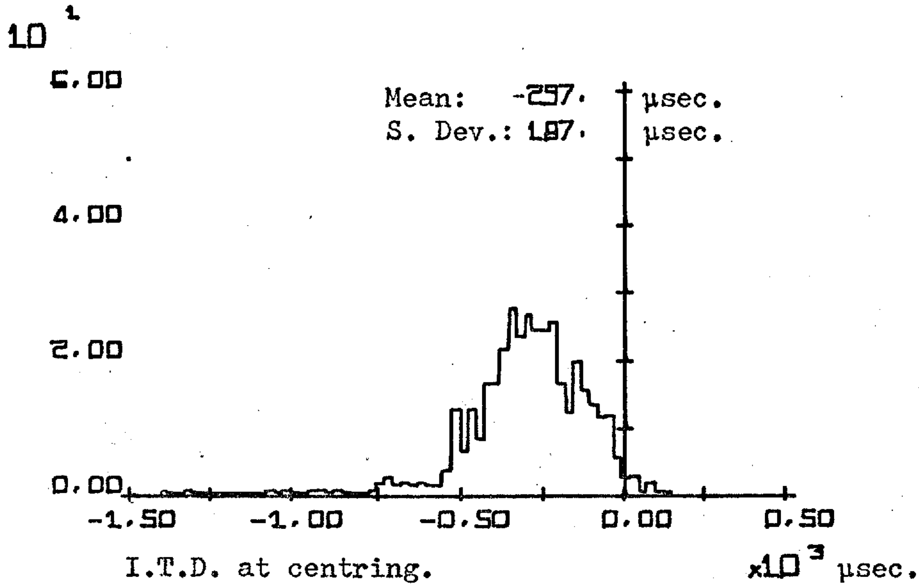


Figure V.8 a. Histogram of binaural centrings without adaptation. 6 subjects, + 10 db. I.A.D..

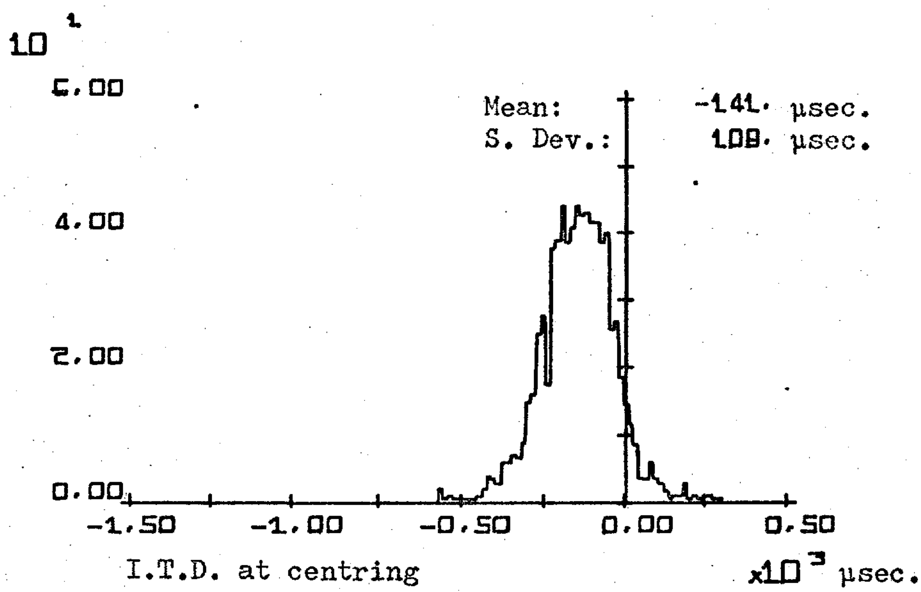


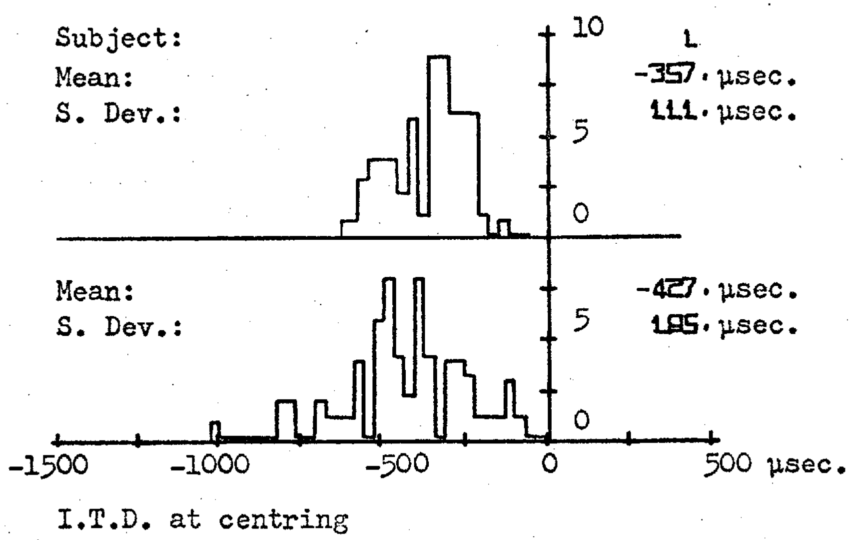
Figure V.8 b. Histogram of binaural centrings with adaptation. 6 subjects, + 10 db. I.A.D.. Redrawn from Figure V.2 a.

The distribution is not significantly multimodal, and would not alone support the multiple image theory that a trading ratio of 30 μsec/db would favour.

Figure V.9 (a and b) details the individual contributions to the previous histogram; in each case the top trace gives the distribution of binaural centring with a +10 db I.A.D., the bottom trace with -10 db I.A.D.

A very interesting point concerning adaptation is evidenced in these distributions: for every subject, the unadapted trading ratio is significantly greater (by a factor of two on the average) than the adapted trading ratio. (For comparison, a table of the individual adapted centring average judgments, is presented with the figure). Previously, the binaural judgment sequence indicated that certain subjects (see subjects no.1 and 3, in figure V.3a) did not adapt to repeated I.A.D. presentations: the facts are now that these subjects adapted very rapidly probably in less than three judgments, and that the adaptation trend could not be detected in the noise. This is an important finding for binaural experimentation, since it now indicates that adaptation effects were reported by every subject and therefore it is almost certainly a feature of binaural experiments with I.A.D.

Figure V.9 reveals another interesting phenomenon in that, in general, the behaviour of a subject is not the same when centring a +10 db I.A.D. image as when dealing with a -10 db I.A.D. image: the two trading ratios are different and moreover, the standard deviations of the judgment distribution are different, being greater in the -10 db I.A.D. than in the +10 db I.A.D. situation; as an extreme case, subjects 4 and 6 do not appear to be able to fuse an image under a -10 db presentation, although they were doing very



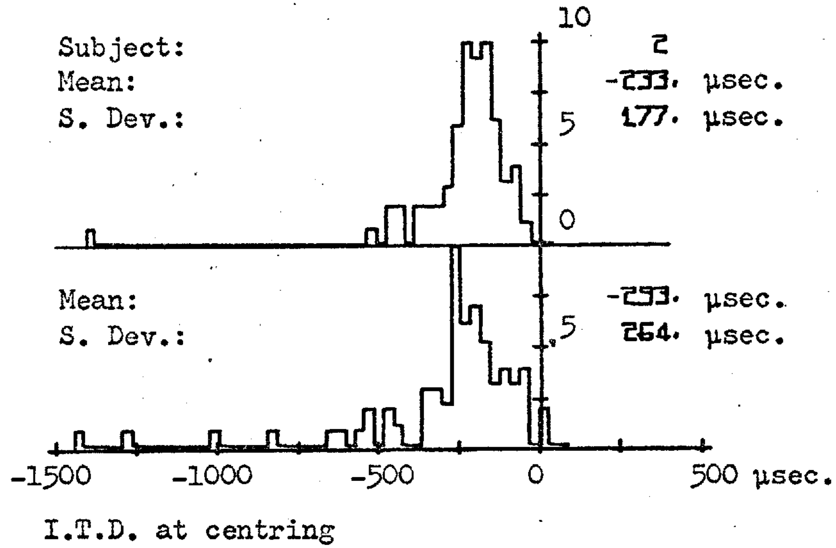
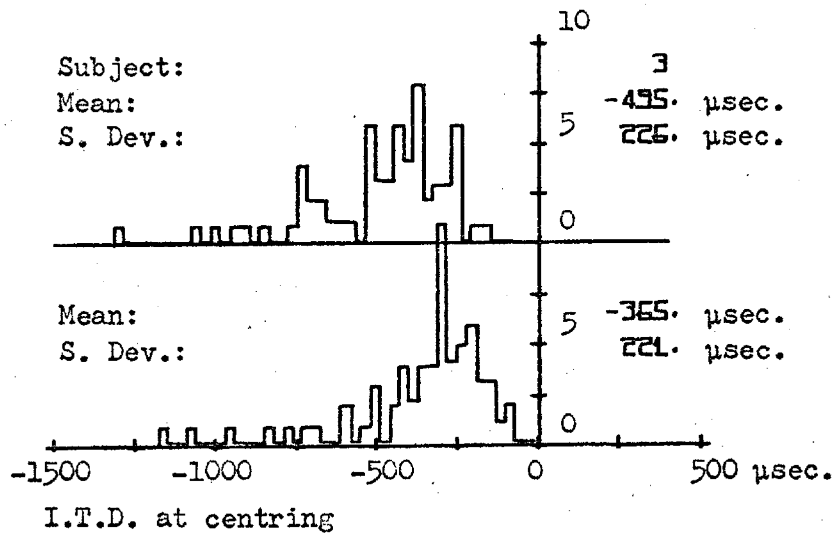
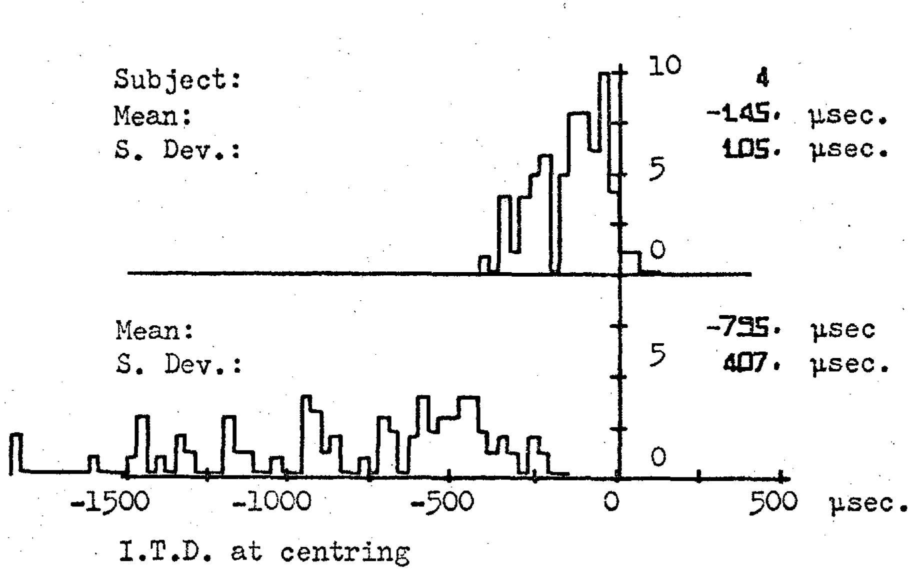


Figure V.9 a. Distribution of unadapted centring judgements. Single clicks; top trace: + 10 db. I.A.D. bottom trace: - 10 db. I.A.D.

The adapted judgement histograms had a mean of:

subject no 1	- 176 µsec.	
no 2	- 159 µsec.	
no 3	- 229 µsec.	





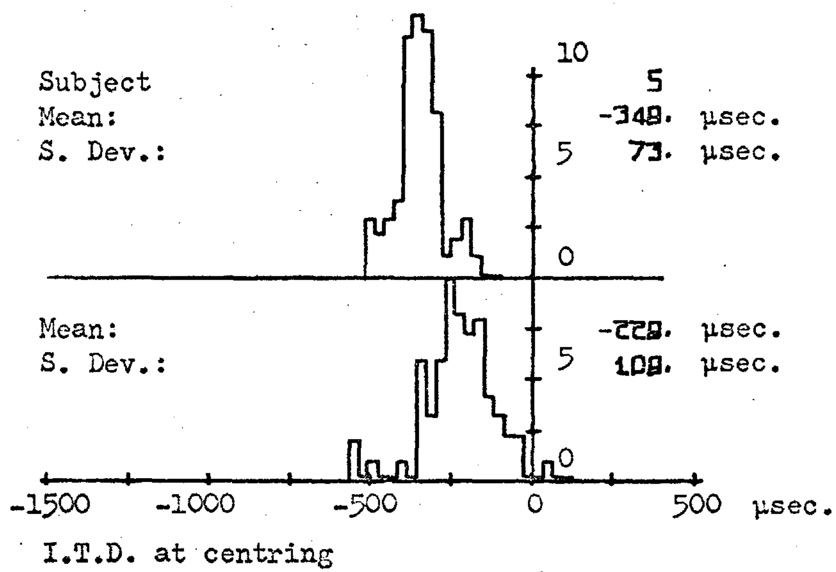
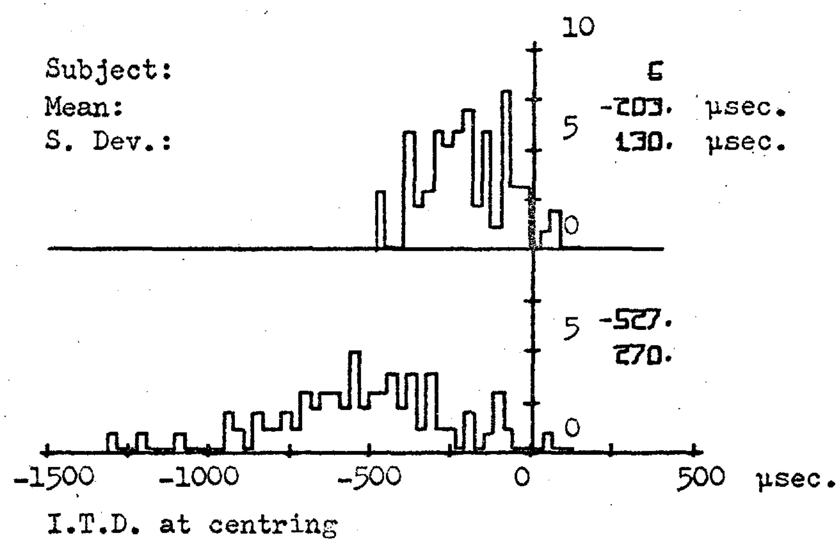


Figure V.9 b. Distributions of unadapted centring judgements. Single clicks; top trace: + 10 db. I.A.D. bottom trace: - 10 db. I.A.D.

The adapted judgement histograms had a mean of:

subject no 4		- 67 µsec.
	no 5	-124 µsec.
	no 6	- 85 µsec.



well in the +10 db I.A.D.** These findings would favour the rule that binaural centring in a I.A.D. situation, is better achieved when the right ear gets the louder signal.

We believe that this dichotomy is genuine, in the sense that it is not associated with peripheral hearing abnormalities, emphasized by the fact that only a few subjects were used in the experiments. Indeed, earlier audiometric measurements of all subjects have shown that their hearing sensitivity was reasonably well balanced. It is possible, that an effect such as recruitment (which mainly shows at high intensity and therefore is not necessarily detected by the Bekesy threshold measurement) may be at the origin of the phenomena: however this is unlikely, since it would imply that the recruited ear is the same one for every subject.

Perhaps a fact that advocates in favour of this preference effect is that the phenomenon is not unprecedented in psycho-acoustic: a right ear preference has been evidenced by other workers, (for example Sanford E. et al. (1971)), who reported that the "right ear" was better than the left one at processing verbal signals presented dichotically with noise; the left ear on the other hand, would do better with tonal signals.

In the event that the dichotomy is genuine, (the two cochlea being well matched) our findings would indicate that the I.A.D./I.T.D. effect is not only related to the peripheral coding of the acoustic

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** To verify that these findings were not due to the headphones themselves, a short experiment was conducted with subject no.4 where the headphones were physically inverted; in this case, he would still fuse with difficulty when the left ear got the louder of the two signals.

waveform, but also to the way this code is interpreted at higher centres which, incidentaly would be consistent with the multiple image theory referred to earlier.

This being the case, the picture of the trading ratio becomes much more complicated since it now involves the participation of higher auditory centres; the possibility that the efferent mechanism, (for which there is a very elaborate cochlear innervation), may also be involved, is not to be overlooked and quite certainly needs further attention.

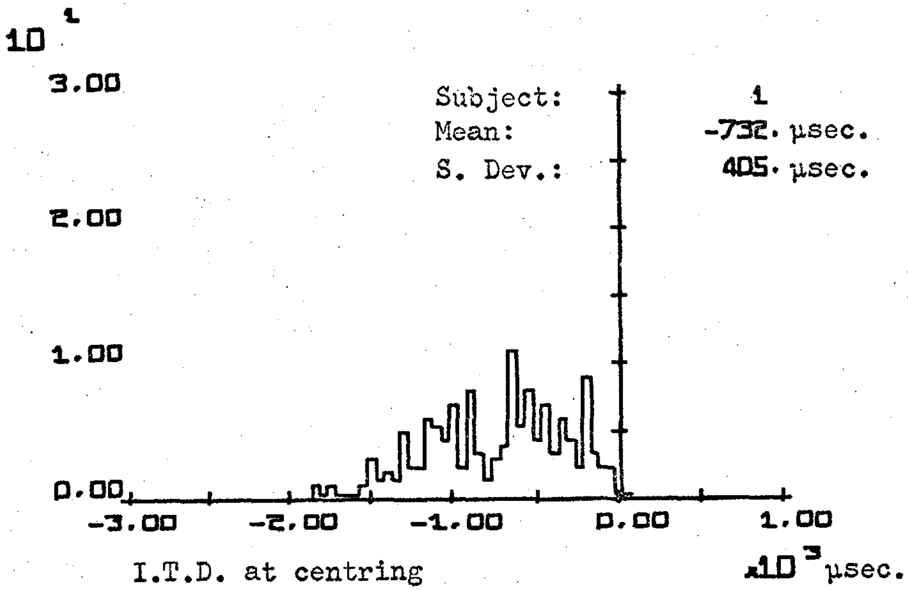
V.4 Centring Experiments with a 20 Decibels I.A.D.

It has frequently been reported that one of the effects caused by the introduction of an I.A.D. was to broaden the perceived acoustic image.(For example:Sayers and Lynn,(1968)). This effect has in general been found to be progressive, the image becoming more diffused as the I.A.D. is increased. There is however a limit to this broadening: from a certain value of I.A.D. onward, the image splits into two components or secondary images. (Harris, (1960)).

Our previous experiments have confirmed this broadening effect; it was found that the standard deviation of the judgment distribution was indeed larger in the 10 db I.A.D. experiments than in the 0 db cases. It was not however possible to demonstrate clearly the existence of secondary images, mainly because of the histogram resolution.

We wish now to report some experiments aimed at evaluating quantitatively the character of the secondary images. We have carried out a set of experiments where the subjects were asked to recenter the acoustic image resulting from the fusion of low-pass filtered clicks (cut-off frequency: 2 Khz) with a deliberately large I.A.D. of 20 db.

This set of experiments was conducted in an adapting (+20 db only) and unadapting situation (+20 db alternated with -20 db I.A.D.). Apart from the value of the I.A.D. itself, every other parameter remained unchanged from the preceding experiment. Again the same control program was used with the same six subjects. The results are reported in figure V.10 to V.14. Figure V.10 (a and b), gives the distribution of centrings for each subject (128 judgments) corresponding to the adapted cases, i.e. the presentation was always



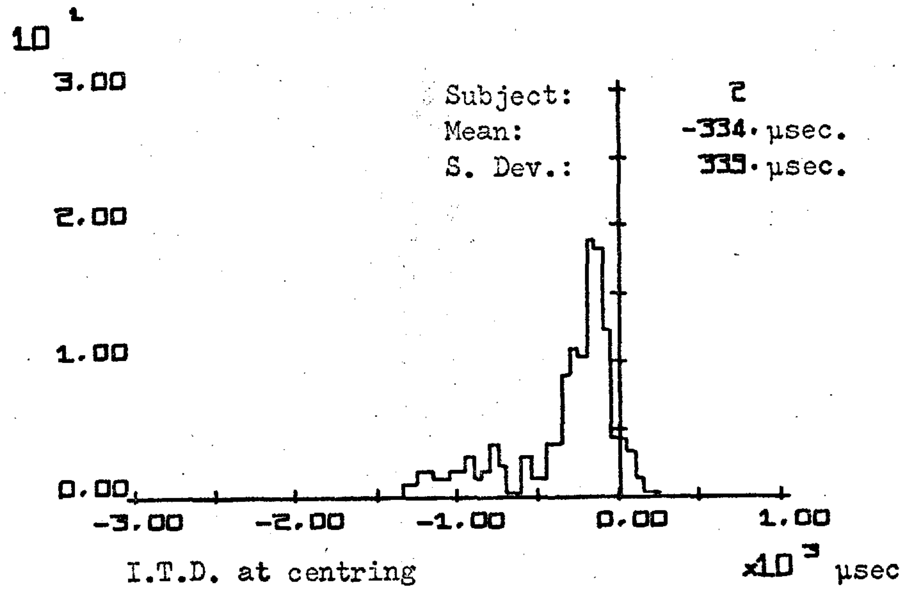
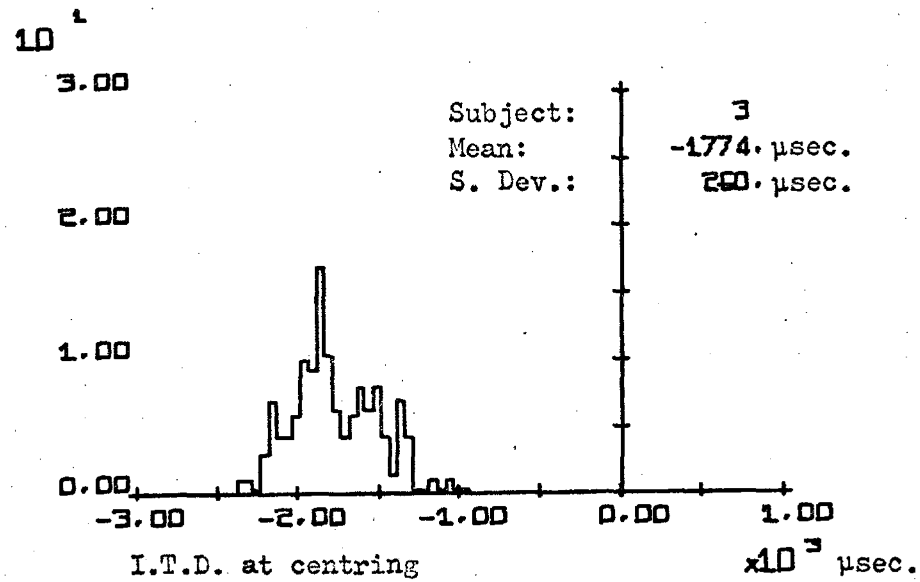
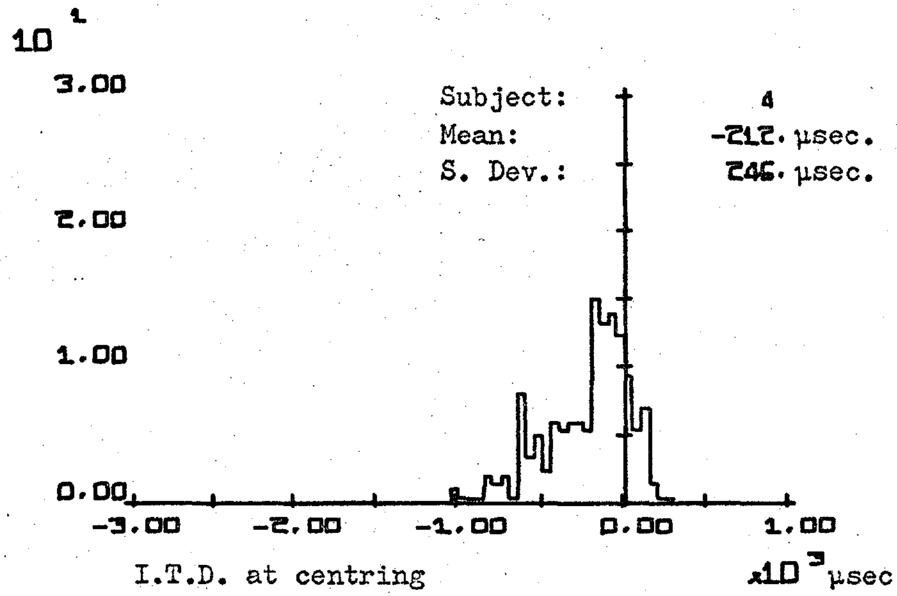


Figure V.10 a. Individual centring judgement histogram, (adapted judgements). Single clicks, 20 db. I.A.D.





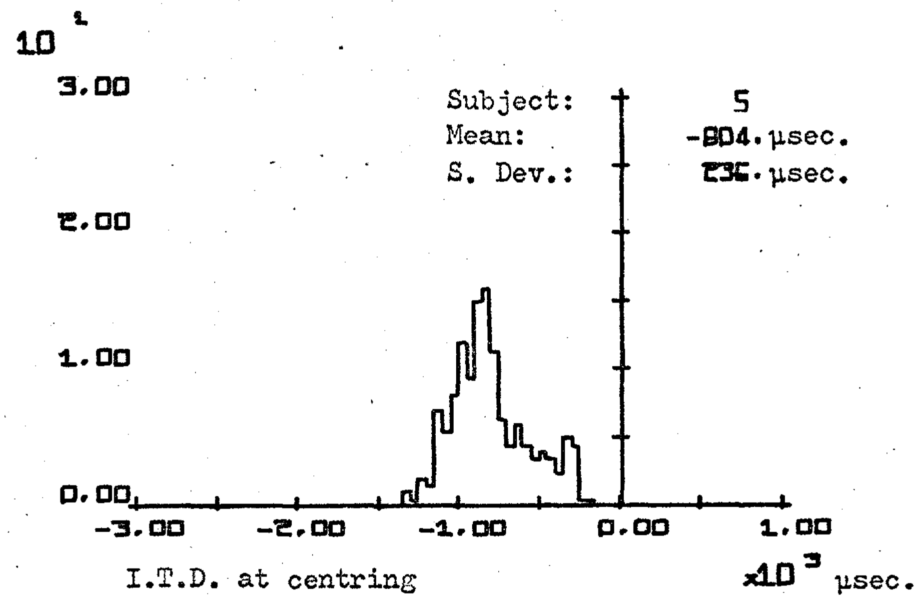
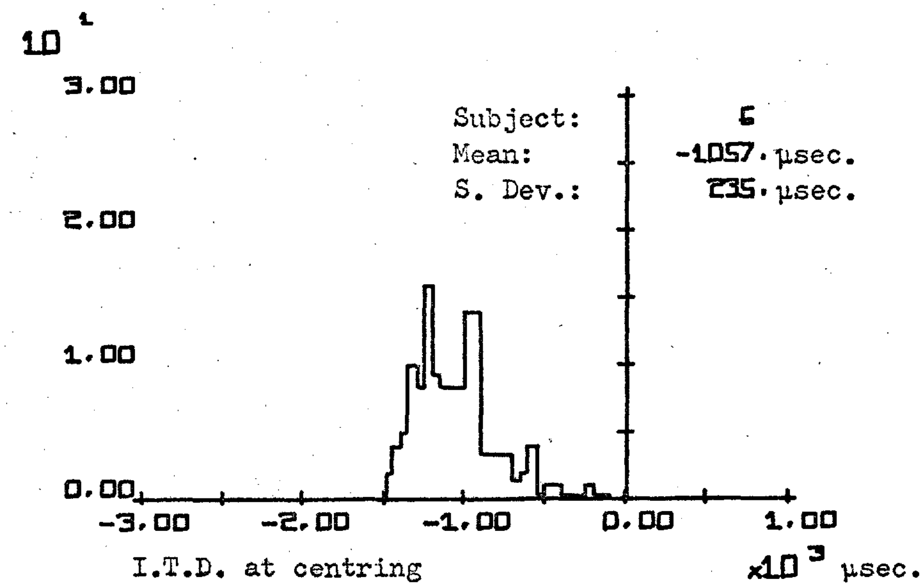


Figure V.10 b. Individual centring judgement histogram, (adapted judgements). Single clicks, 20 db. I.A.D.



with a +20 db I.A.D. Figure V.11 gives the group distribution of the complete set of judgments detailed in figure V.10, while figure V.12 shows the averaged binaural sequence.

Figure V.13 (a and b) shows the individual distribution of the "unadapted" judgment experiment (+ and - 20 db): the top traces relate to the +20 db while the lower ones refer to -20 db I.A.D. Figure V.14 shows the corresponding grouped judgment histograms.

V.4.1 Evidence of Multiple-Images

The results of this set of experiments are rather conclusive with respect to the view that there are multiple coexisting images associated with binaural fusion with I.A.D. For that respect the adapted centring judgment distribution (figure V.11) is particularly illustrative since three peaks can be distinctly identified near -200 μsec, -1000 μsec and -1800 μsec. In part these peaks are obviously related to some individual contribution: the -200 μsec peak comes mainly from subjects 2 and 4; the -1000 μsec, from 5 and 6, and the -1800 μsec from subject 3. However the facts are that certain subjects (subject no.1 and particularly subject no.2) reported multi-modal centrings at corresponding peaks of the group histogram, thus indicating the perception of two distinct images.

The relatively regular spacing of the modes in the group histogram would indicate that the multiple images arose in the region of 1 kc, and that the subjects centred the images corresponding to the first, second and third rarefaction displacement of the basilar membrane at that particular place frequency. It is worth mentioning

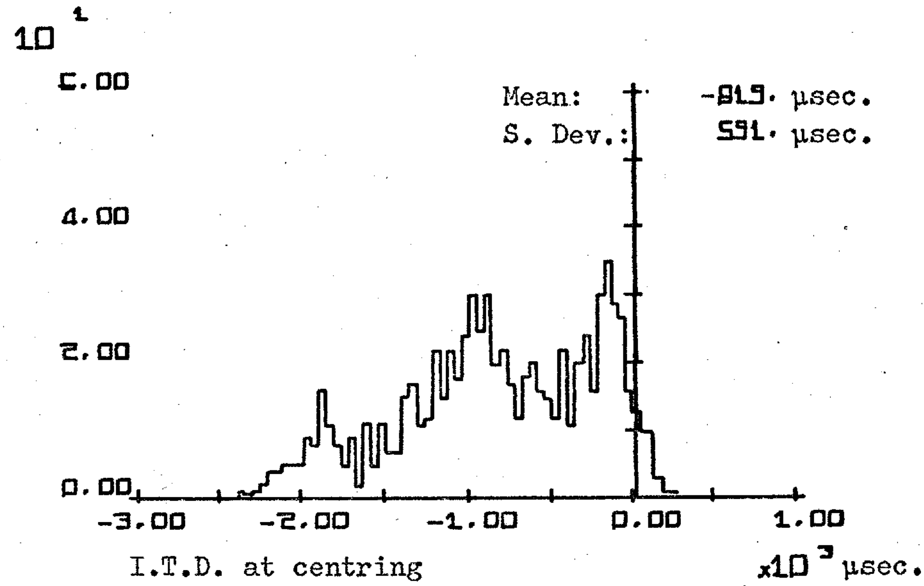


Figure V.11 Adapted judgement histogram.
Single clicks, 20 db. I.A.D.. Combined
histogram of figure V.10 a and b.

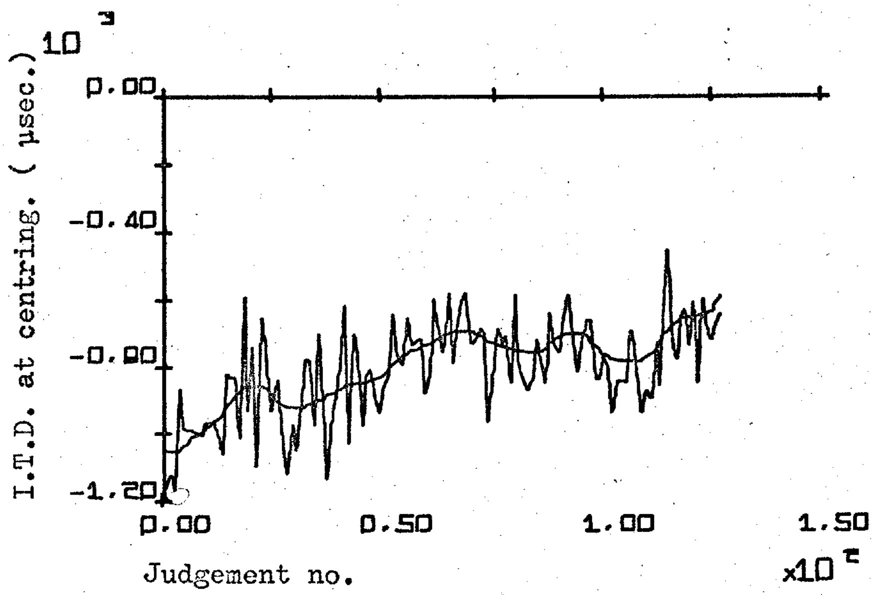
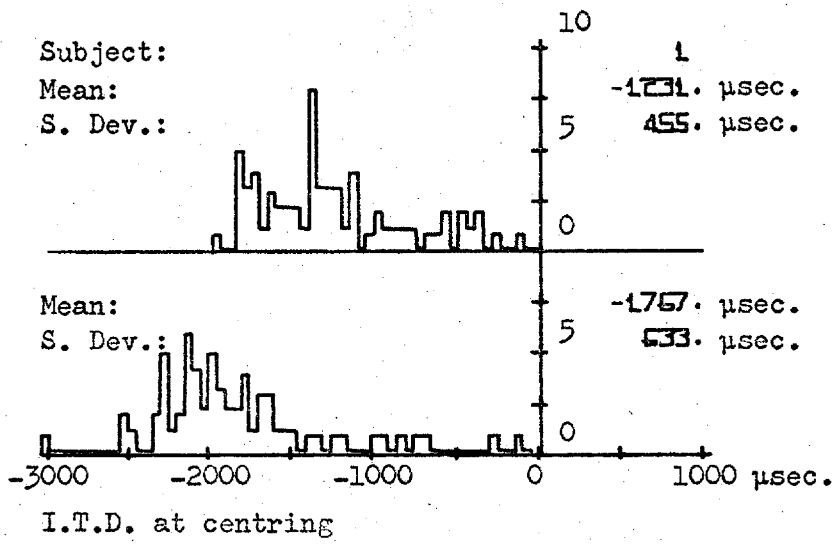


Figure V.12. Averaged binaural judgement sequence.
Single clicks, 20 db. I.A.D..



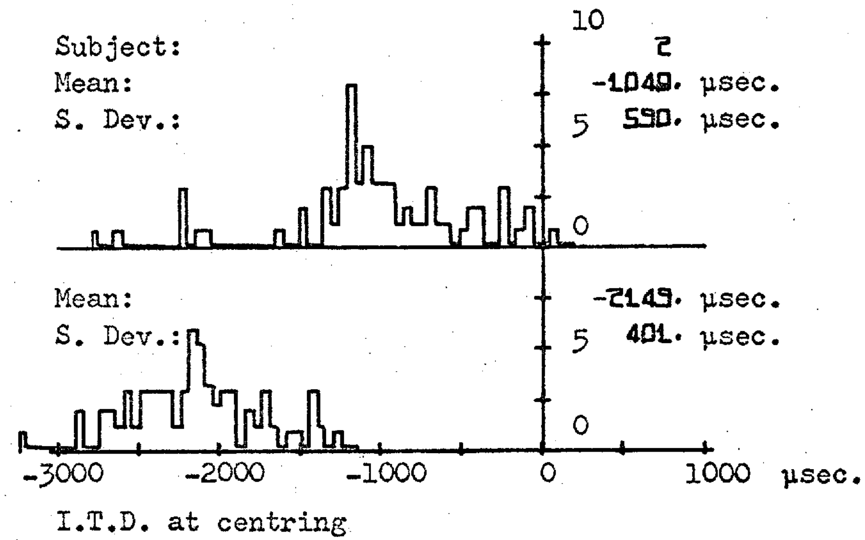
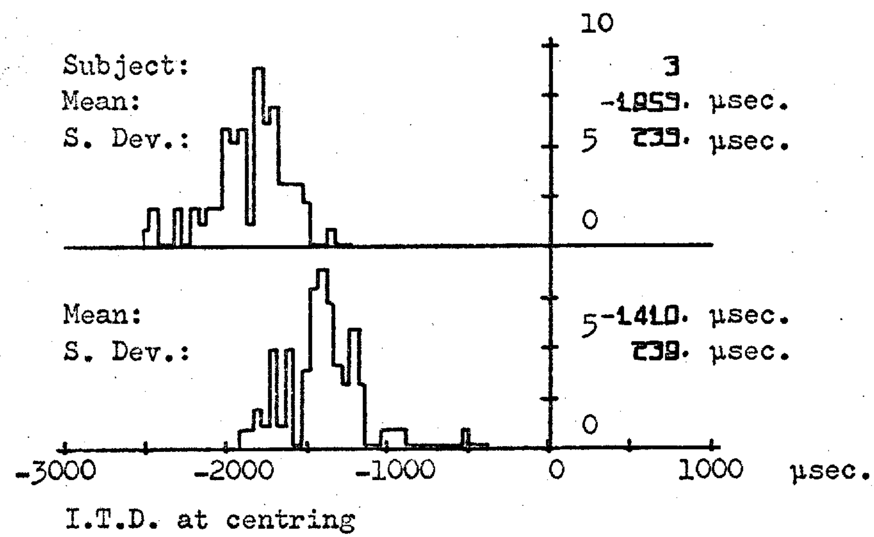
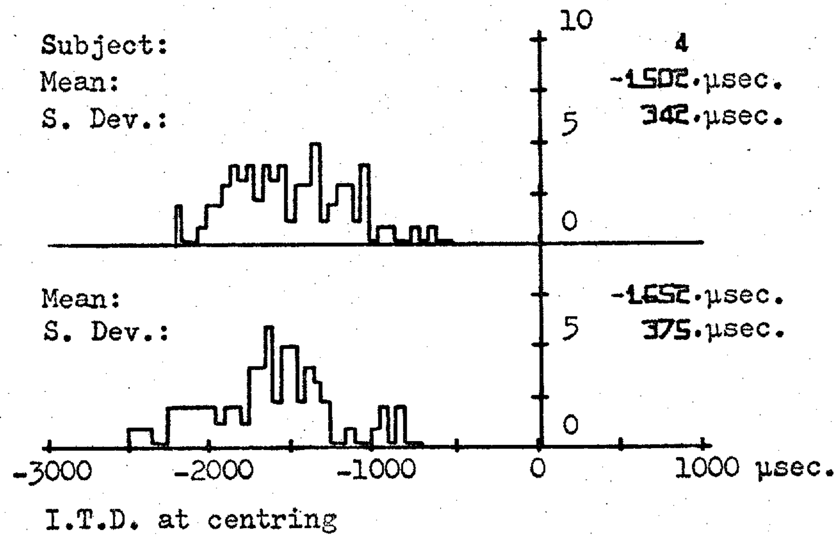
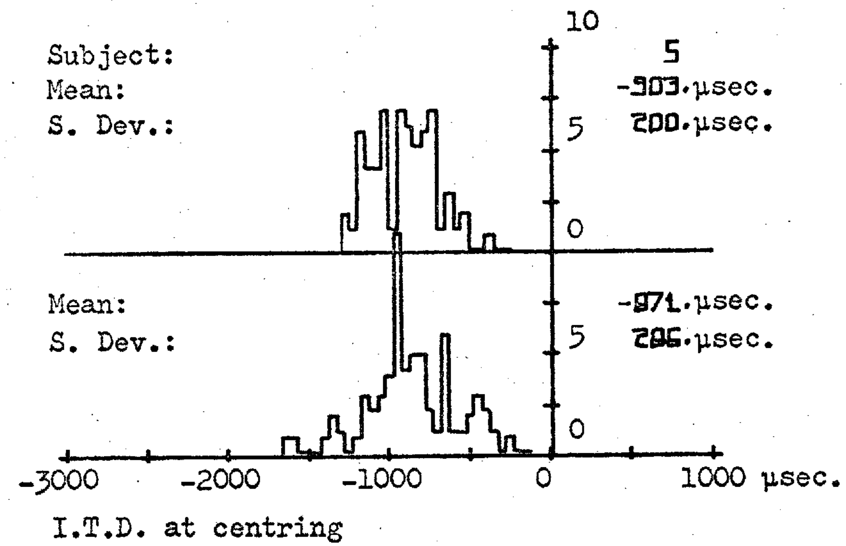


Figure V.13 a. Individual un-adapted judgement histogram. Single clicks, ± 20 db I.A.D..







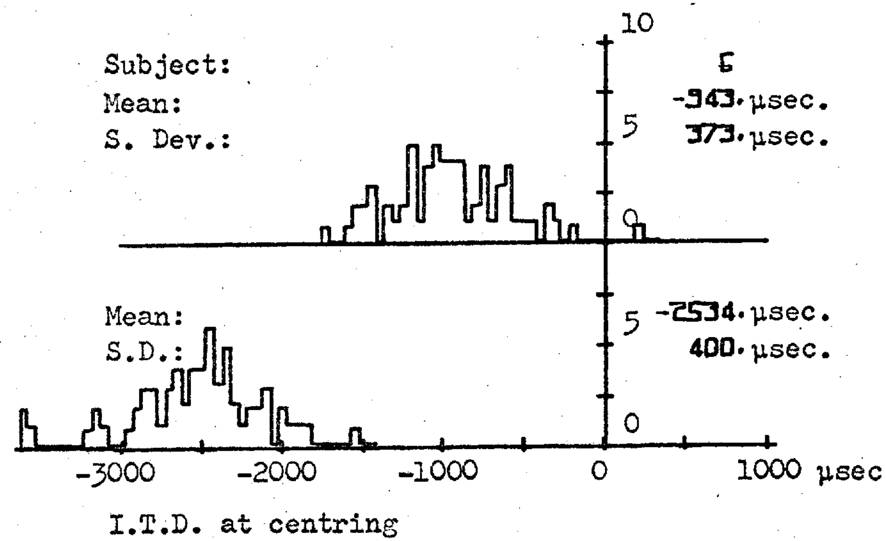


Figure V.13 b. Individual un-adapted judgement histogram. Single clicks, ± 20 db. I.A.D..

Figure V.14. Combined centring judgement histograms of figure V.13.

Figure V.14 a: + 20 db. I.A.D.

Figure V.14 b: – 20 db. I.A.D.

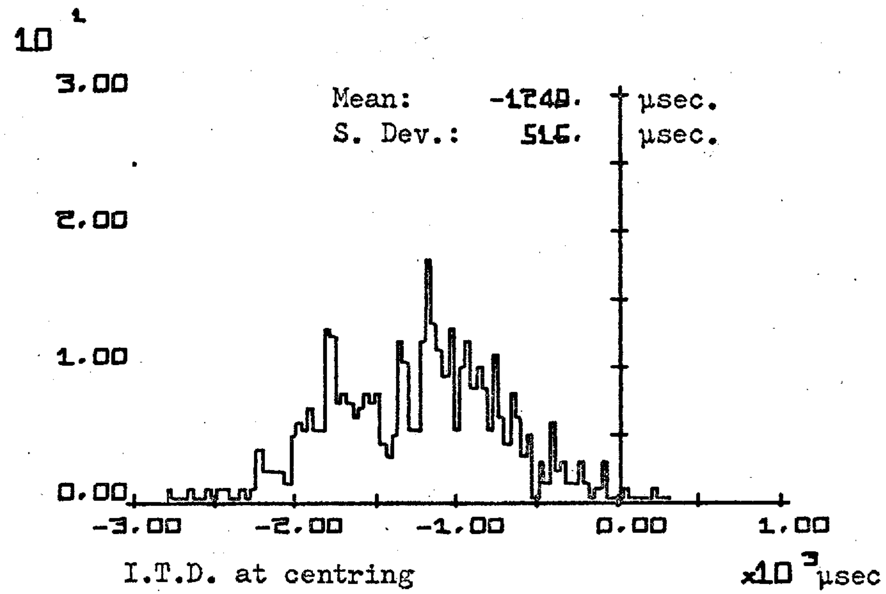


Figure V.14 a.

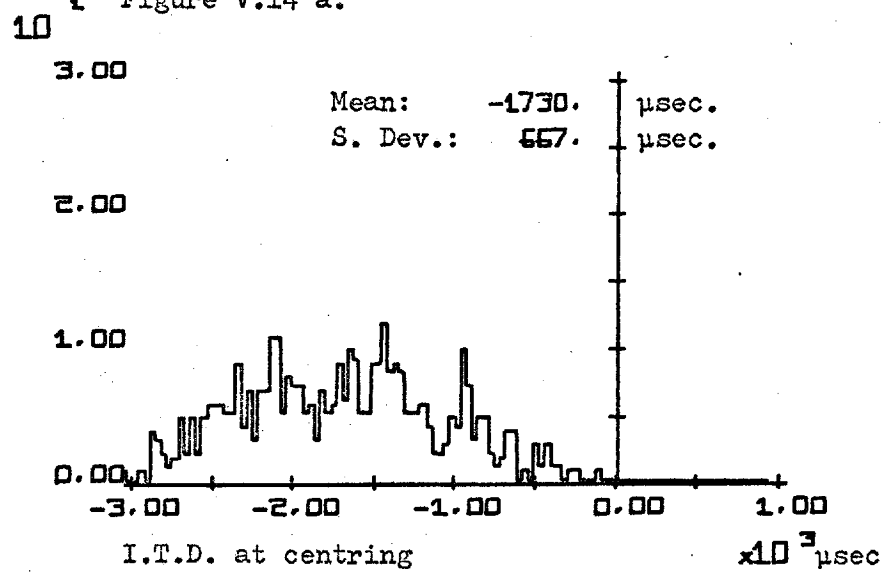


Figure V.14 b.

that this particular region of the basilar membrane has been previously referred to as being dominant in binaural perception of wide-band transients. (Sayers, (1966))

The distribution of un-adapted centring judgments (figure V.14) also evidences the existence of multiple images in the region of -1000 µsec and -1800 µsec, showing that the 1 kc place frequency region has been selected to fuse the acoustic image.

V.4.2 Adaptation Effects

As far as the behaviour of the group as a whole is concerned, the averaged binaural centring sequence (figure V.12) demonstrates that adaptation occurs in the course of the experiment. However, contrary to the situation presented by the previous set of experiments (10 db I.A.D.), the adaptive effect is not general: for subjects nos. 3, 5 and 6 the mean of the adapted judgment distribution (figure V.10 a and b) does not significantly differ from the mean of the unadapted one. (figure V.13 a and b).

For the case where adaptation occurred, a comparison between the adapted and unadapted judgment histogram of the group (figure V.11 versus figure V.14a) would favour the multiple image theory: the -200 µsec mode in the adapted distribution totally disappears in the unadapted judgment histograms which suggest that, in this particular experiment, adaptation partly consisted in a shift of attention from an image (-1000 µsec) to another (-200 µsec); subjects no. 2 and 4 are good examples of this behaviour. (See figure V.10 and V.13).

The fact that this type of adaptation relates to the way the perception of multiple images is achieved, raises an important point;

it would seem that the shift of attention to another image is certainly the mechanism that underlies the process that enables masking and unmasking of acoustic sources, (i.e.The Cocktail party problem, Cherry, 1962)), a process that physiologically might involve the efferent system, the centrifugal pathway.

It is interesting to note that the proposed view (on the unmasking mechanism being relevant to the adaptive behaviour evidenced here) could also be used to interpret the un-adaptable behaviour of certain subjects, since they would simply appear to be able to unmask effectively one of the secondary images.

Finally going further along this line, it may also be possible to include the I.A.D./I.T.D. effect into a more general framework, by considering it as a special case of unmasking competing images.

V.4.3 The Trading Ratio

The present set of results shows a trading ratio that covers a range of values much wider than the previous set of experiments had revealed. Indeed, the various distributions of centring judgments would comfortably cover the range of trading ratios reported by previous workers: from 10 µsec/db (subject no.4, figure V.10) up to 95 µsec/db (subject no.3, figure V.13).

Our experiments reveal an important fact on this question: rather than being uniformly distributed in the range of values mentioned earlier, the distribution of the set of centring judgments (figure V.11) suggests that the trading ratios tend to group themselves around some preferred values (the modes of the histogram). This phenomenon, analogous to a quantification process, could be predicted by the multiple image theory, on the assumption that the 1 Khz place frequency had been chosen to perform the cross comparison between the two cochlear neural activities.

V.5 Origin of Binaural Adaptation

Adaptation is an important issue when dealing with the problem of studying the perception of I.A.D. From an experimental point of view, the question matters since adaptation has been shown to alter significantly the perceptual behaviour of subjects in the process of doing a centring experiment.

However adapatation raises also an interest from a theoretical point of view, particularly as far as its origin is concerned. In the following section we will investigate this matter by looking at some of the physiological factors that are known to be associated with a form or another of auditory adaptation.

V.5.1 Peripheral Adaptation

i) Middle Ear Adaptation

One of the functions of the middle ear cavity is to act as an impedance matching device between the outer and inner ear. The structure is not however as passive as the arrangement of ossicles and ligaments would suggest, and accordingly its role is not confined to a transfer of energy from one medium to another; indeed a protective function is achieved via the ossicular chain by the action of two small muscles: the tensor tympani and the stapedius muscle. These muscles acting synergistically can provide a low frequency attenuation (below 2 Khz) that may be as much as 40 db (Wiggers, H. (1937), quoted by Mountcastle, W.B. (1968)).

Until recently these muscles were known to be activated only as a reflex upon exposure to intense sounds. However, experiments in cats (Carmel, P.W. and Starr, P. (1963)) have revealed that they also reacted to low intensity acoustic stimuli, to which they could provide an attenuation of up to 18 db in the 200 to 4000 Hz band.

Of a particular interest to the question of binaural adaptation are the facts that, in these circumstances, the muscles have been shown to habituate to stimuli: the activity maximal at onset was found to decrease in 30 to 90 minutes. In man, the acoustic reflex shown to be dependent on the type of stimuli (Lilly, D.J.(1964), Mills and Lilly,(1971)), may have however a smaller accomodation time constant. More recent measurements of the middle ear mechanical impedance suggest a time constant in the order of 5-6 minutes, for a 1000 Hz octave band noise. (Brasher et al. (1969)).

In order to make the middle ear muscles responsible for the binaural adaptation present in an I.A.D. experiment, one must also assume that the level of habituation is different in each ear so as to compensate for the original I.A.D. Physiologically, this is not impossible since there seems to be a monaural excitatory pathway for the acoustic reflex; although it is consensual, the reflex is more sensitive to ipsilateral stimulation. It therefore would appear that the stapedius and tensor tympani muscles have the necessary properties to achieve binaural adaptation being monaurally sensitive to the level of input stimuli (Moller, A.R.(1962)) and displaying habituation.

This may be a very attractive proposition but there is however an important fact that would not favour this hypothesis. Figure V.4a has revealed an adaptive time constant of 85 sec and it definitely falls short of the 6 minutes referred to earlier for the acoustic reflex; although they do not refer to the same stimulus condition, the difference seems to be too large for the two time constants to relate to the same phenomenon. A second point of importance here is the fact that in the same experiment (20 db I.A.D.) certain subjects displayed adaptation while others did not and that in a previous experiment (10 db I.A.D.) every subject adapted to the stimuli. The middle ear accommodation theory could not easily account for this sort of behaviour. It therefore appears that, alone, it is not an appropriate theory to explain binaural adaptation.

It must be remembered that we have provided only indirect indications about the middle ear activity not being responsible for binaural adaptation. Because of the complexity of the mechanism involved, only direct measurements could provide a definite answer to that question. Simultaneous binaural middle ear impedance measurements would be suitable for that purpose, and we propose that future research should be directed along this line.

ii) Cochlear Adaptation

For most sensory mechanisms, adaptation can be traced to some extent to processes within the receptors. Recording the action potentials from the efferent nerve of various receptors shows that, with continued application of a stimulus, the frequency of discharge declines. (Ochs, S.(1966).

The rate of decline varies according to the type of receptor and the type of stimulus involved. In the auditory system, it has not been possible up till now to record the activity of the receptor themselves, the hair cells, and therefore their adaptation characteristics could not be assessed; however the discharge pattern of a single nerve fibre in the cat's auditory nerve (the first relay after the receptors) has been studied in detail by Kiang,(1965) and some adaptive features have been evidenced.

Figure V.15 shows the time course of the changes in the rate of discharge of two units with high and low characteristic frequency (C.F.). In both cases the stimuli were continuous tones at the C.F. Visual inspection indicates that a time constant of 1 minute (figure V.15a) and 4-5-minutes (figure V.15b) is associated with the adaptive process.

As pointed by Kiang himself, (Kiang,(1965) p.77), "The time course of the adaptation of unit discharges is comparable with the time course of loudness adaptation in normal human subject". Indeed this would fit our findings as well and therefore would imply that binaural adaptation would originate at the cochlear level.

Apart from the fact that human and cat's receptor may differ, there is however a very important distinction between the two situations: there is the fact that the stimuli are widely different in terms of susceptibility to adaptation. Kiang, (in the experiment just reported) used continuous sinusoidal excitation at the C.F. of the fibres, therefore producing a very large neural output with the fibre concerned; at the other end, we used filtered transients at the rate of 20 pps; moreover, we programmed a 4 seconds resting period between each judgment which, in any event, would enable the

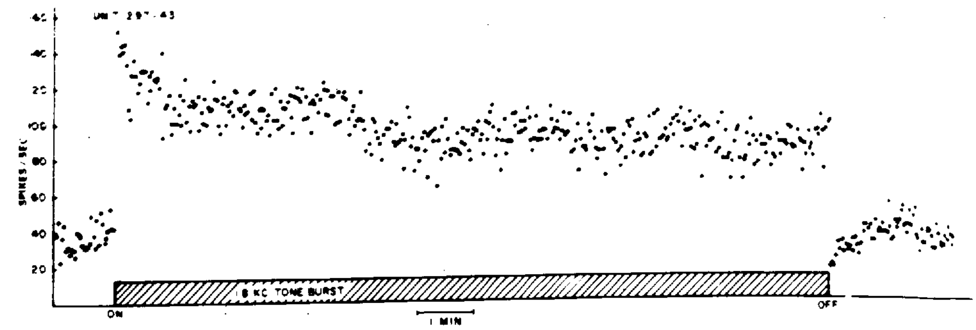


Figure A. Changes in the rate of discharge of a unit with low CF (1.8 kc) when a tone burst of 13 minutes' duration is presented.

The data were divided into successive 1-second samples. Counts were made of every other 1-second sample. Stimulus: tone burst, 2.5-msec rise-fall time, −50 db. The shaded horizontal bar represents the duration of the tone burst.

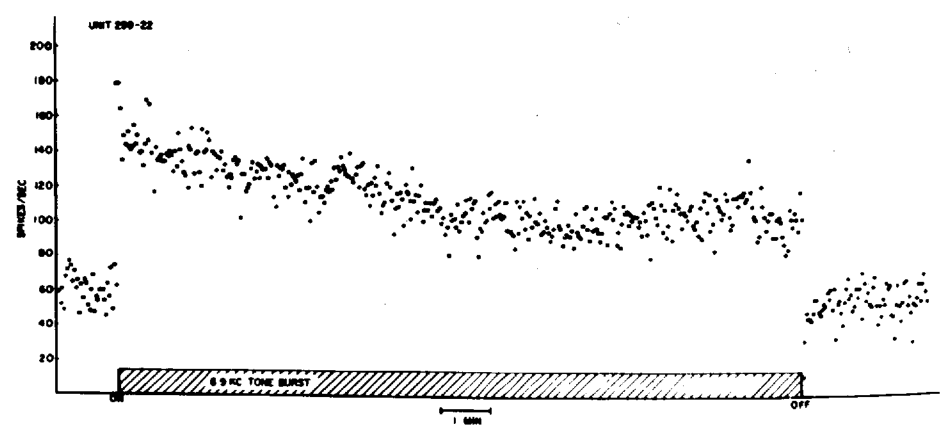


Figure B. Changes in the rate of discharge of a unit with high CF (8.9 kc) when a tone burst of 13 minutes' duration is presented.

The data were divided into successive 1-second samples. Counts were made of every other 1-second sample. Stimulus: toneburst, 2.5 msec rise-fall time, −70 db. The shaded horizontal bar represents the duration of the tone burst.

Figure V.15. From Kiang, (1965).

receptors to recover should any adaptation have occurred: as suggested by physiological recording, a similar type of stimulus would not lead to adaptation (figure V.16).

We therefore have to conclude that the adaptative behaviour as evidenced in a binaural experiment probably does not originate at the level of the receptors. The fact that it is not likely to result from middle ear fatigue would seem to rule out any interpretation in terms of peripheral accommodation. It therefore leads us to look at higher auditory centres as being responsible for the phenomenon.

V.5.2 Central Auditory Adaptation: Habituation[1]

We will now examine some of the possible neurophysiological mechanisms associated with the behavioural aspect of auditory attention and see if they can be related to with the phenomenon of binaural adaptation.

The neurophysiological bases of habituation have been substantiated by recording of evoked potential at various level of the auditory pathway, from cochlear nucleus to cortex: indeed at all levels, a continuous acoustic stimulation is accompanied by a diminution of the activity evoked at the beginning of the presentation. (Baust et al. (1964a)). The idea that habituation could originate from a central mechanism emerged when it was found that the evoked

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[1]Cortical and sub-cortical adaptation is also referred to as "habituation", underlying, at the neurophysiological level, the psychological state where attention is not being paid to a sensory input.

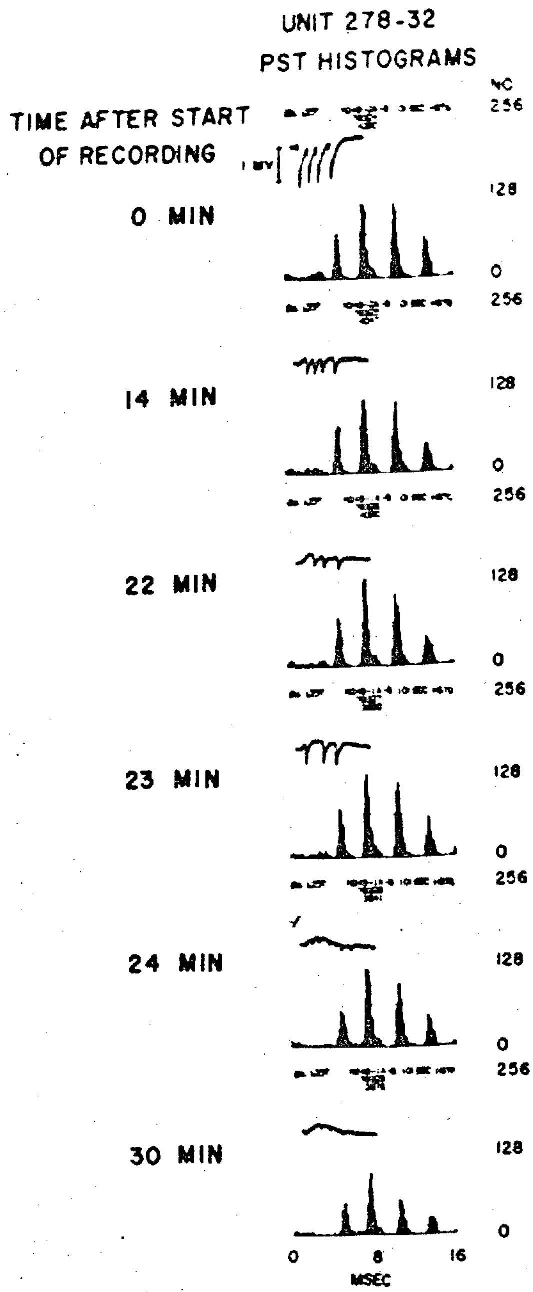


Figure V.16. A demonstration of the stability of spike discharge patterns for a single unit over a long period of time.

PST histograms are of 1-minute samples of data taken from a 30-minute record. The insets in each histogram show 10-millisecond samples of spike discharges synchronized with click presentations. When the recordings began, spikes were more than a millivolt in amplitude but gradually decreased until at about 23 minutes after the start of recording there is an abrupt increase. Thereafter the spikes decreased in size rapidly until they were too small to trigger the computer. Some spikes were missed in the computation of the bottom histogram. CF: 0.43 kc; stimuli: 10/sec clicks, −50 db.

From Kiang, (1965).

potentials at all levels of the auditory pathway, were dependent on the psychological state of the animals (cats) from which the recordings were taken: click evoked potentials were bigger when the animals were in a state of awareness than when they were asleep. (Baust et al.(1964a)). Since this could be demonstrated using clicks with a very low repetition (1 per 4 seconds), a potentially low fatiguing stimulus for the receptor involved, it then became apparent that the phenomenon was due to a centrally controlled peripheral operation.

The role of the efferent fibres (the olivo-cochlear bundle of Rasmussen) was questioned along this line, especially since Fex,(1962) found that excitation of those fibres had an inhibitory action on the afferent cochlear activity; more specifically Desmedt,(1962) found that activation of the olivo-cochlear bundle could produce an inhibition equivalent to a decrease of 25 db on the acoustic input. Further studies made by Galambos,(1965) led to the conclusion that the cochlear efferent system (from cochlear nucleus to cochlea) was not primarly responsible for a change in evoked potential in attentive state and a form of gating at the cochlear nucleus via a centrifugal pathway was therefore hypothesized. However, better controlled experimental procedure rejected this theory (Worden,(1966)) and revealed that no change in evoked responses correlated with sleep and attention states could be detected peripheral to the inferior colliculus, provided that the middle ear muscles were made inactive. (Berlucchi,(1967)).

These various experiments revealed several points of interest and potentially relevant to binaural adaptation:

A) the role of the complex efferent system is not simply of gating the sensory information to the brain in an unselective manner. The current view on this question is that it plays a role in shaping the sensory input and is involved in peripheral processing of the neural signal. It could indeed be used in a frequency selective mechanism, since the efferent fibres are associated with characteristic frequency (tuning curves) and project tonotopically in the cochlea. (Fex,(1962)). It therefore would appear that a form of habituation via the efferent system could indeed be very complex (being frequency dependent for instance); recent recordings (Kitzes and Buchwald,(1969)) in the cochlear nucleus have shown that at this level, habituation (with middle ear muscles inactive) could be detected as a change in the shape of the evoked potential which would favour a frequency selective mechanism.

It appears therefore that the efferent system cannot be ruled out of the habituation process; however its exact function in habituation has not been established and one can only be speculative on the subject. From the various experiments performed in the last decade, a few of which have been reported here, it appears quite clearly that the effect of the efferent fibres in habituation is subtle and in any cases much less marked than that which results from the middle ear muscle activity.

B) The effect of middle ear muscle activity in attention and habituation is markedly defined: dependence of the cochlear response on state of attention or sleep could be demonstrated on cats with normal ear but not on cats with middle ear muscle tenotomized. (Baust,(1964a)). This dependence on the psychological state also suggests that the middle ear activity does not arise only from reflex action, but that it is centrally controled; indeed it was found that in cats, the threshold for the reflex was lower during attention state (63 db) than during sleep. (73 db). (Baust,(1964b)).

These authors found further evidence in favour of a central control over the middle ear muscle activity and its relation to habituation: the tympanic reflex (in cats) could habituate to the stimulus (in 5 to 10 minutes) and subsequently deshabituate when the animal was presented an arousing stimulus (a mouse).

This activation of the ear muscles from higher centres of the auditory pathway suggests that they are not only involved in a protective mechanism but that they could also be used in a form of peripheral processing of the auditory signal; the implications of this function in binaural hearing have been discussed by Lawrence, (1965). Given that the ear muscles can be centrally controlled, this author proposed that an independent monitoring of each ear's myogenic activity would enable the brain to peripherally affect the inter-aural amplitude difference. There is now some evidence that suggests that this is indeed the case: reporting on binaural recording of cochlear potential, Legouix and Foret, (1970) observed that the ossicular muscle contraction showed differences in both sides, suggesting an independent control of the muscles. It is worth mentioning that a mechanism of this type could be of great help at solving the cocktail party problem (Cherry,(1962).

It appears now that we have nearly all the necessary elements to explain binaural adaptation in terms of a central habituation process: central habituation seems to be mediated by a control of the middle ear activity; in turns this activity could be independently controlled at the site of each ear. One has simply to assume that the level of habituation is amplitude dependent to relate the prolonged exposure to I.A.D. to a situation where binaural adaptation occurs.

V.5.3 Conclusion

In this section we have examined some auditory mechanisms potentially relevant to binaural adaptation and on which physiological recordings have already shown adaptability. It appears that binaural adaptation cannot be related to a simple peripheral fatigue mechanism (receptor fatigue or middle ear muscle fatigue): the time constant involved or the type of stimulus used does not seem to lead to the form of peripheral habituation known physiologically.

The possibility that the central auditory mechanism may be involved in the process has been investigated in relation to the efferent system and the centrifugal control of the ear muscles. The physiological evidence now available would favour the latter to be responsible for binaural adaptation.

Binaural adaptation would therefore originate from a central mechanism controlling peripherally the level of the acoustic input; in this context it is perhaps not surprising to see that binaural adaptation time constants are so widely different from subject to subject and, as we have observed, from day to day with the same subject. This matter also stresses the importance of interpreting very carefully the results of inter-aural amplitude differences: the inter-aural amplitude difference at the outer ear may very well be different from the amplitude difference at the cochlear level, in which case it would not be surprising to see the reported trading ratio varying so widely.

No doubt, the question about the role of the middle ear muscles in binaural hearing needs to be answered and our propositions verified before pursuing studies on the perception of I.A.D.

V.6 Conclusions

This chapter has been concerned with the study of the variability associated with the psycho-physical measurements of the trading ratio.

We have been able to identify at least two processes relevant to this question.

The analysis of the time dependence of binaural centring with I.A.D. revealed an important underlying adaptive feature that, in part, accounts for the variability of the trading ratio. With medium-valued I.A.D. (10 db) adaptation was reported by every subject (in a group of six) and found to alter the value of the trading ratio by a factor of nearly two. To assess the significance of the phenomenon a further set of experiments was performed with a larger group of subjects (20 subjects): adaptation was confirmed and an average accommodation time constant of 85 seconds was estimated from this study.

An analysis of the various physiological mechanisms potentially relevant to binaural adaptation led to the conclusion that the middle ear muscles, monaurally controlled be a centrifugal pathway, were the most probable source of binaural accommodation.

That the acoustic reflex may be involved in the perception of I.A.D. certainly causes serious problems for the psycho-physical measurement of the trading ratio; binaural adaptation mediated by the ear muscle involves two independently controlled centrifugal mechanisms and therefore introduces sources of inter-aural difference. The question now arises about the possiblity that cochlear I.A.D. may be different from the outer ear I.A.D., a phenomenon that would bring further variability in the psycho-physical measurement of the trading ratio.

A second major source of variability that we have identified in our experiments relates to the perception of multiple images. The phenomenon had been predicted by the neural activity correlation model of Monro,(1971), where the individual images were associated with consecutive rarefaction phases of the basilar membrane displacements; we could clearly demonstrate this property when a large value of I.A.D. (20 db) was used, although there are some indications that the phenomenon occured with smaller I.A.D. (10 db).

The existence of multiple images associated with I.A.D. has also been demonstrated by other workers; Hafter and Jeffress,(1968), have been able to train their subjects to identify two images in 9 db. I.A.D. experiments, and related these images to two different trading ratios: 9 µsec/db and 30 µsec/db. Recently Carier and Hafter, (1971), proposed that these images were associated with two distinct binaural sub-cortical mechanisms, one dealing with time difference, another with amplitude difference; higher centers would subsequently deal with combining the two separate effects. This view has also been supported by other workers (McFadden et al. (1971)) who also pertinently made the observation that intensity and time were not rigorously traded in I.A.D. experiments: a recentred I.A.D. image does not sound like a centred image without I.A.D.

This dual pathway theory can be physiologically substanciated: Langford,(1971) distinguished in the superior olivary complex two groups of binaural cells; in the medial olive a majority of "δt" cells were found to be sensitive to I.T.D. but little to I.A.D.; in the lateral olive, a majority of "δI" cells was found to be more sensitive to I.A.D. than I.T.D.

We believe however that this particular theory (i.e. the dual pathway for time and intensity) is not sufficient to explain our findings: we not only found two, but rather three coexisting images in one set of experiments (20 db I.A.D.), a fact that the correlation theory can account for.

From both points of view it would nevertheless appear that the virtual shift of an image introduced by the presence of an I.A.D. is not a purely peripheral phenomenon (as was suggested earlier by Lynn and Sayers,(1970). Of a more complex kind, it would involve the participation of higher centres in the interpretation of the amplitude difference. This theory, supported by Monro,(1971), is in accordance with our findings.

CHAPTER VI

BINAURAL INTERACTION OF A PULSE WITH A PULSE PAIR

VI.1 Introduction

We have shown in the previous chapter that a prolonged exposure to an inter-aural amplitude difference was generally accompanied with binaural adaptation.

It has also been suggested that this phenomenon originated from the acoustically unbalanced nature of the signal, since alternate presentation of positive and negative I.A.D. did not produce adaptation.

We will now look at the case of a different type of acoustic stimulus, frequently used in binaural experimentation and that also leads to a binaurally unbalanced situation. This particular stimulus consists of a pulse pair fed in one ear, and a single pulse fed in the other and therefore is an unsymmetrical binaural input; from the analysis presented in the previous chapter, such auditory signal is likely to be associated with dynamically changing perceptual behaviour. The present chapter will relate to this question.

VI.2 Experimental Conditions

The click pattern used to study the interaction of a pulse with a pulse pair is shown in figure VI.1.

In our experiment, this signal was low pass filtered at 2 Khz and set at a repetition rate of 20 pps. The peak sound level of pulse A and C was 75 db re .0002 dynes/cm^2; pulse B, was set at 65 db.

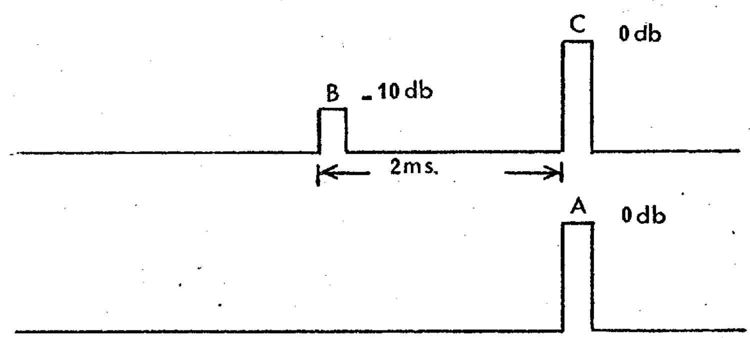


Figure VI.1 Pattern to study the interaction of a pulse with a pulse pair.

Using the automated experimental technique referred to earlier, the position of pulse A was set by the computer, at a random A-C interval in the range ± 600 µsec. The B-C spacing remained constant.

On presentation of the signals, the subjects were instructed to recentre the perceived acoustic image by repositionning pulse A; the recentred image was then recorded as the A-C interval, being positive when C was leading. Each subject had to recenter 128 binaural presentations; a four seconds resting period was programmed between each binaural judgement. The same six subjects, (referred to in chapter II with the Bekesy audiometric test) collaborated to the experiments.

VI.3 The Binaural Judgements

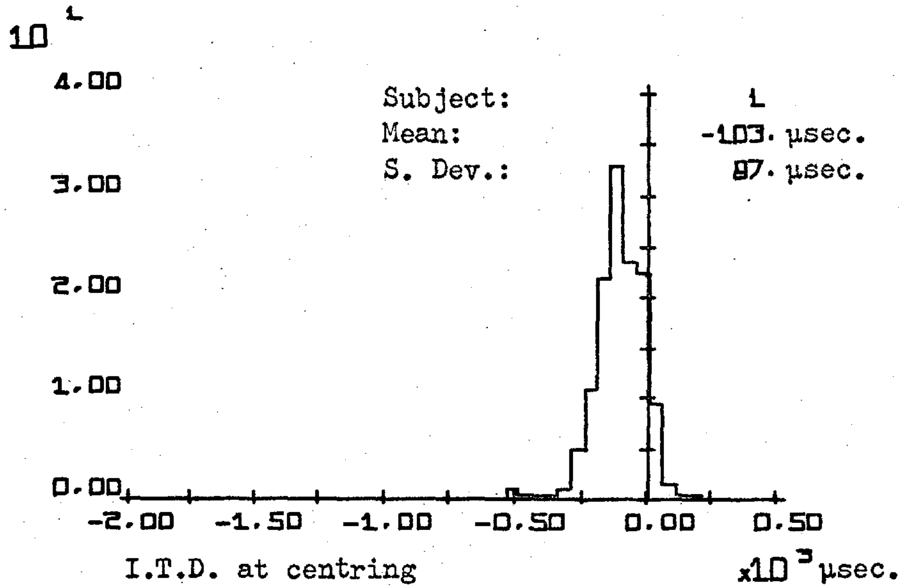
Figure VI.2 (a and b) shows the individual histograms of the binaural centrings reported by each subject; figure VI.3 shows how these group into a single distribution. The unimodal character of the group histogram as well as the value of the mode itself, (near -200 µsec), suggests that in this experiment the A-B image has not been perceived and that fusion only occured following an A-C interaction. In general the individual histograms also supports this view.

Figure VI.4 shows the average binaural judgement sequence computed in a manner explained earlier. (i.e. a weighted sum of the sequences of each subject.)

The curve, similar to the I.A.D. adaptation waveform, also underlies an adaptative process. The progressive shift of the binaural centrings during the experiment follows a pattern resembling the time course of the (adapted) I.A.D. judgement sequence, (figure V.4a), suggesting that in both cases the same mechanism was operative: i.e. a peripheral modification of the signal via the middle ear muscle activity.

Consequently it would appear that the conclusion drawn earlier in this section (fusion occured with A.C pulses only) would not relate to the experimental situation depicted by the click pattern of figure VI.1. More explicitely, in the event that the ear muscles are activated differently in each ear, the pulse pattern after adaptation may very well be perceived as:- 0 db, -20 db, -10 db (amplitude ratio of A.B.C. pulses) rather than the -0 db, -10 db, 0 db ratios before adaptation.

Quantitatively we can however only speculate on this question, since middle ear activity has not been binaurally monitored during the



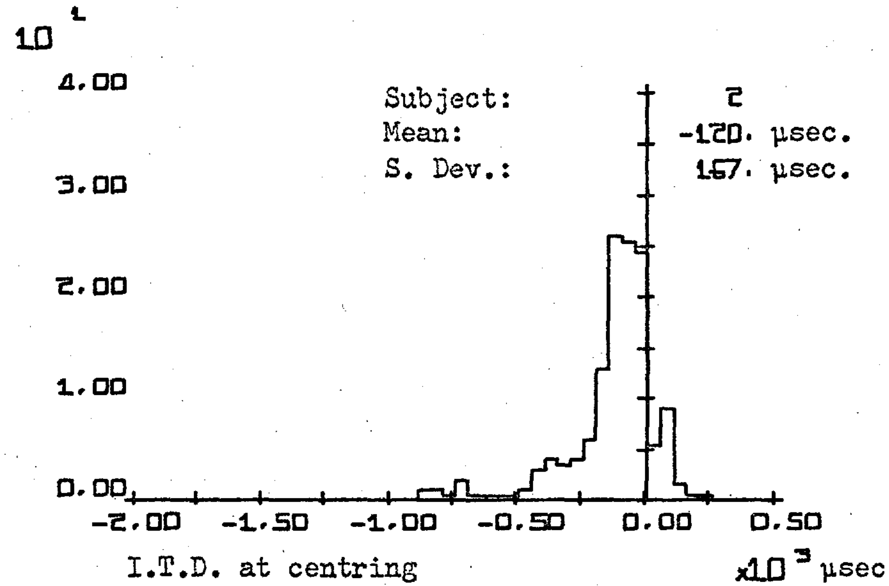
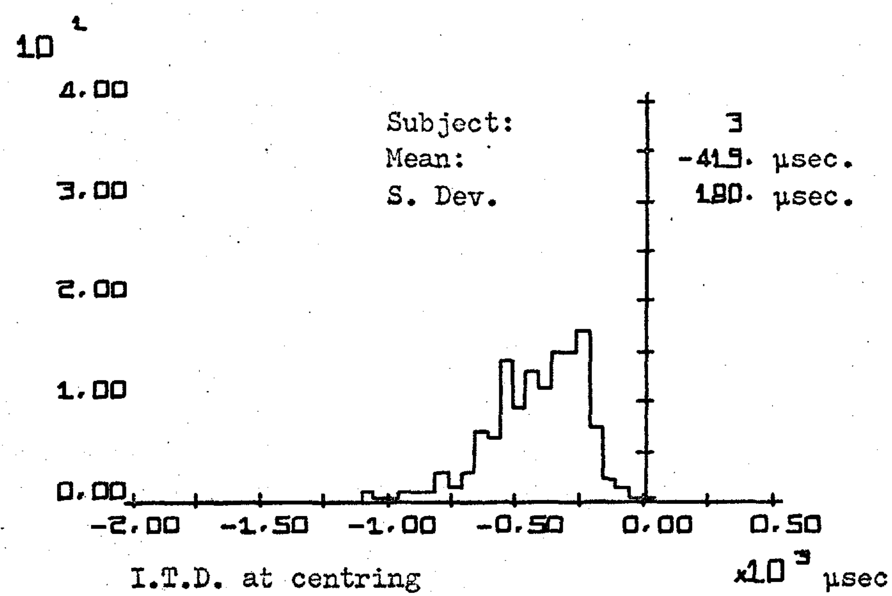
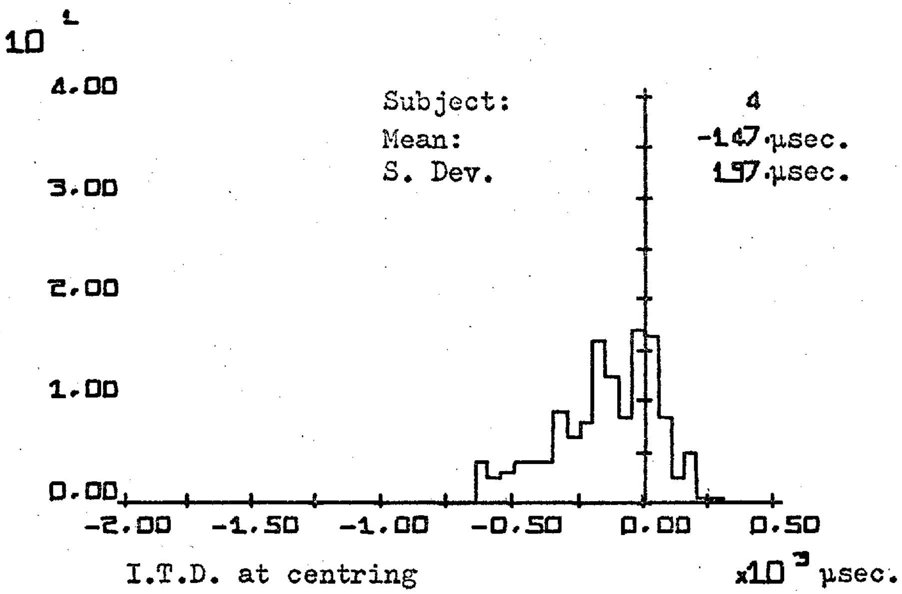


Figure VI.2 a. Individual centring judgement histogram. Interaction of a pulse with a pulse pair.





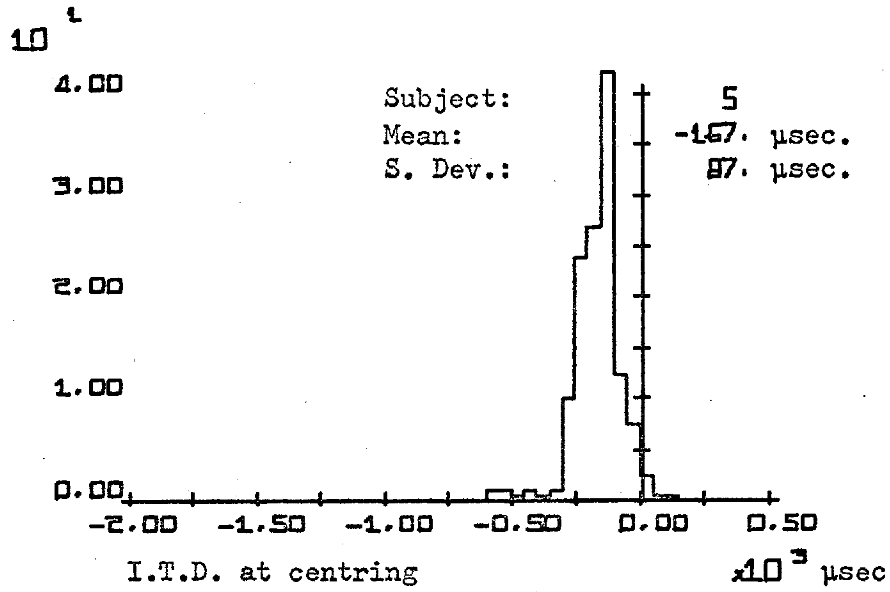
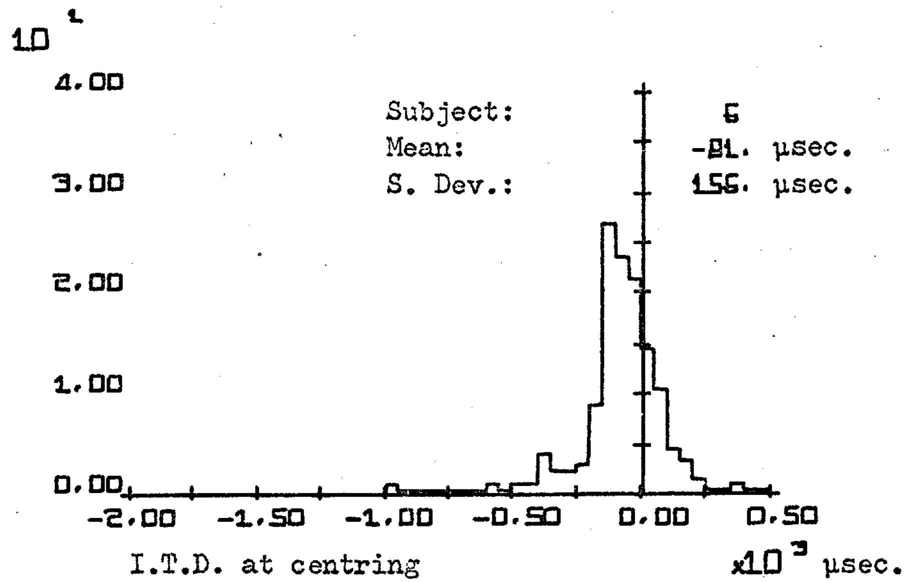


Figure VI.2 b. Individual centring judgement histogram. Interaction of a pulse with a pulse pair.



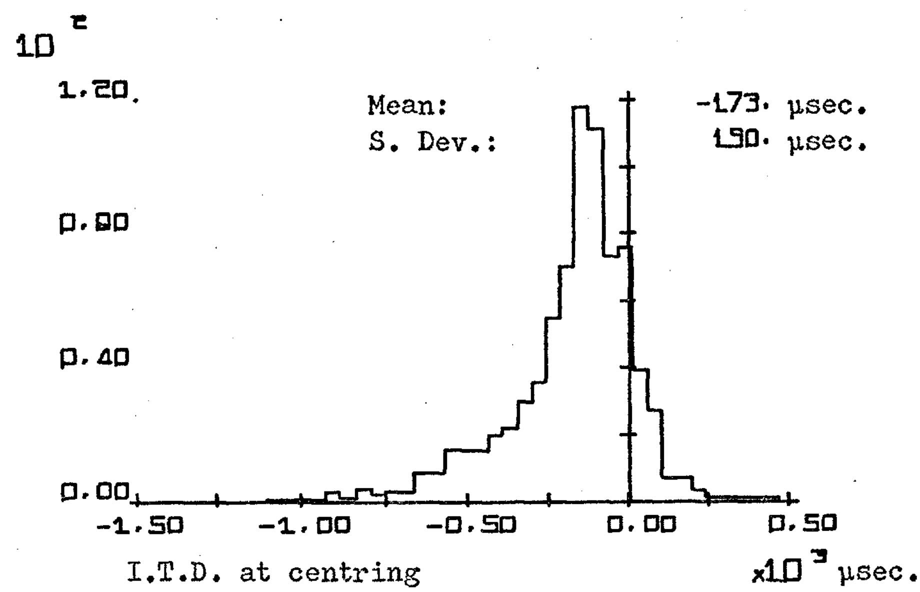


Figure VI.3. Combined histogram (6 subjects, 768 judgements) of binaural centrings. Interaction of a pulse with a pulse pair.

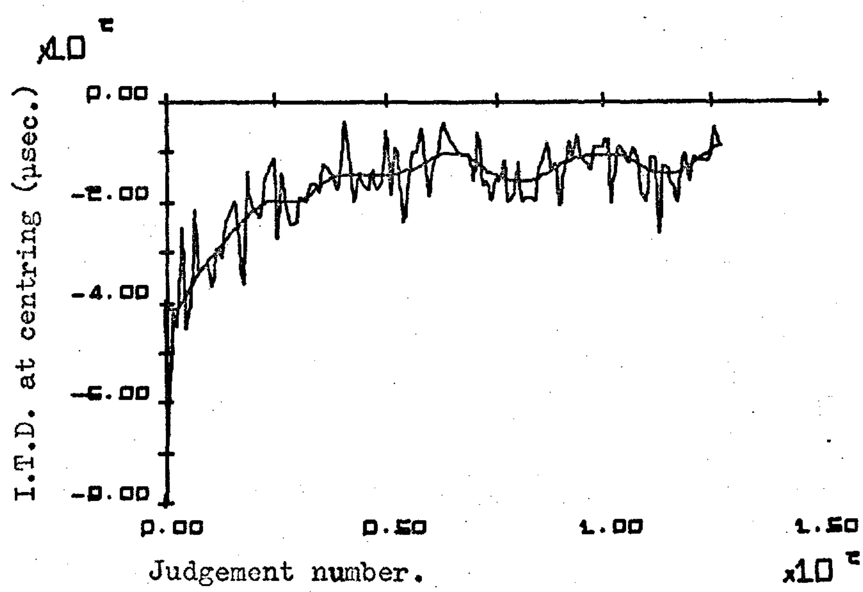


Figure VI.4 Averaged binaural judgement sequence; sequences from 6 subjects were averaged.

experiment; for the moment it is therefore not possible to determine exactly under which conditions the A.C image has not been perceived, for it is not possible to assess what were the "cochlear" ratios, of the A.B.C. pulses.

Nevertheless assuming that we are dealing with the same mechanism present in the I.A.D. experiments, it should be possible to obtain the distribution of un-adapted centring judgements and presumably describe the interaction of the original pulse pattern of figure VI.1; the technique, used in the previous chapter, would simply be of alternating the acoustic inputs so that the long term average of the sound intensity is the same for both ears. The following section relates to this question.

VI.4 The Unadapted Centring Judgements.

The technique described in the previous chapter to study unadapted binaural judgements in I.A.D. experiments, has been applied to investigate the interaction of a pulse with a pulse pair. An experiment was conducted with the same group of six subjects; each subject had 128 binaural presentations where he was asked to recenter the perceived acoustic image. At the first, third,.... presentation, the pulse pair was fed to the right headphone, while at the second, fourth,.. the pair was presented to the left headphone. Every other parameter remained unchanged from the previous set of experiments (section VI.2).

Figure VI.5a shows the averaged sequence of odd numbered binaural judgements corresponding to the right ear pulse pair presentations; the sequence does not show any significant adaptation, unlike the sequence in I.A.D. experiments of the same kind. (Figure V.7).

Figure VI.5. Averaged sequence of binaural judgements. The pulse pair was alternately fed to the right and left ear at successive presentations. Figure a: sequence of odd numbered judgements. Figure b: sequence of even numbered judgements

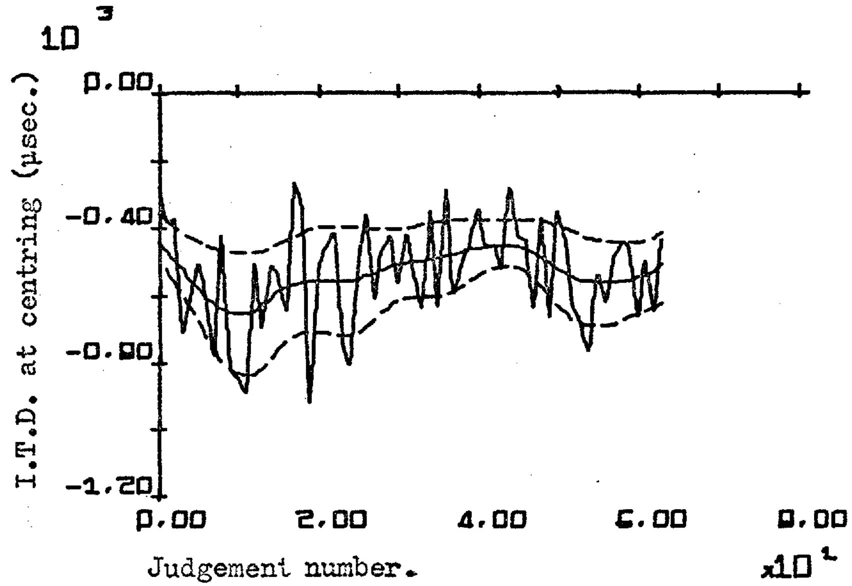


Figure VI.5 a.

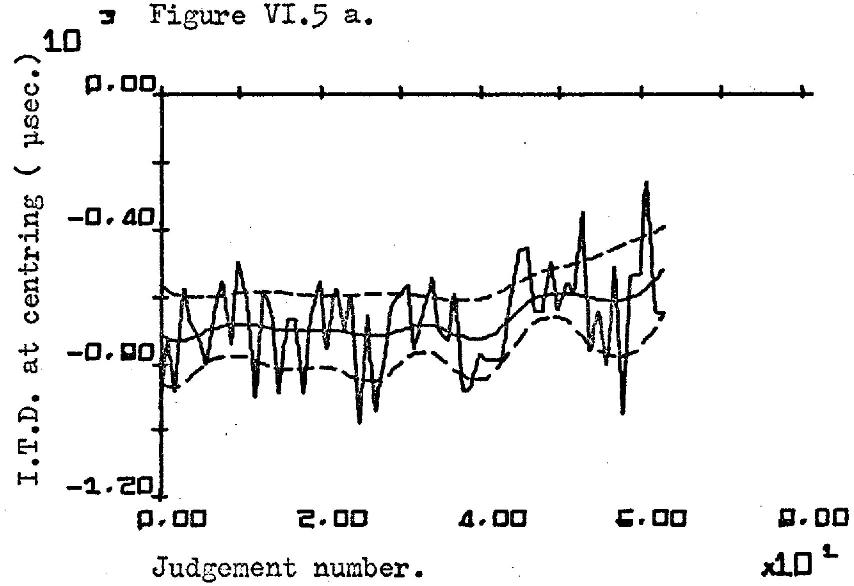


Figure VI.5 b.

This similarity therefore suggests that in both cases the adaptation process related to the same mechanism.

The binaural judgement distribution (of the whole group) that relates to this unadapted sequence is shown in figure VI.6, while figure VI.7 details the individual contributions.

Comparing the various group distributions (figure VI.6) we report the following observations:

i The adapted and unadapted judgement distributions are manifestely different from each other. The differences (figure VI.6a and VI.6b) suggest that adaptation does not only affect the mean of the distribution but that it also alters the distribution itself.

ii From the unadapted judgements histograms, it appears that the A.B image is not perceived in a consistent fashion since it does not produce a well defined peak in the region of -2000 µsec.

iii The A.C. image, when perceived, (even numbered judgements histogram) is shifted towards the virtual A.B image by some 200 microseconds. One can consider this shift as an I.A.D. effect where pulse C would be perceived louder than pulse A.

iv The distribution of odd numbered binaural judgements (pulse pair to the right ear) does not seem to relate to an A.C or A.B image but rather to a combination of both.

The complex perceptual behaviour reflected in these observations does not seem to be easily interpretable in term of a simple binaural interaction mechanism. In particular, this is due to the difficulty of visualizing how the pulse pair is being mechanically analysed along the basilar membrane and subsequently coded neuraly, while taking into account the receptor's logarithmic sensitivity and refractory properties. The matter is further complicated when interpreting binaural interactions since it becomes necessary to

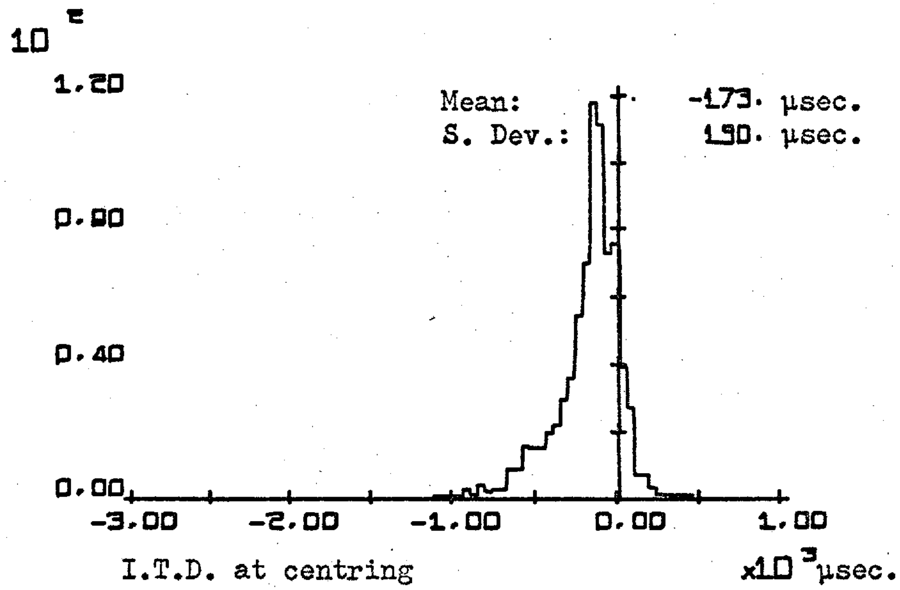


Figure VI.6 a

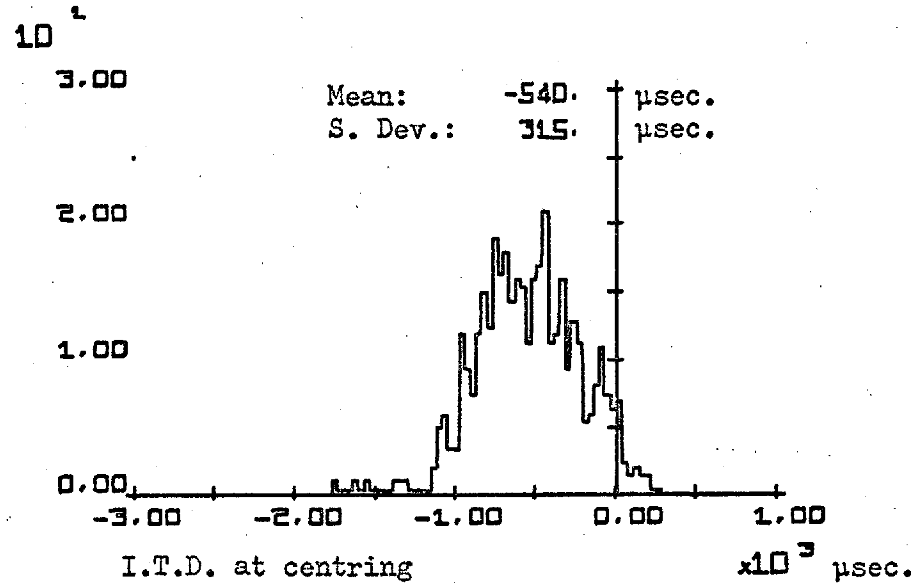


Figure VI.6 b

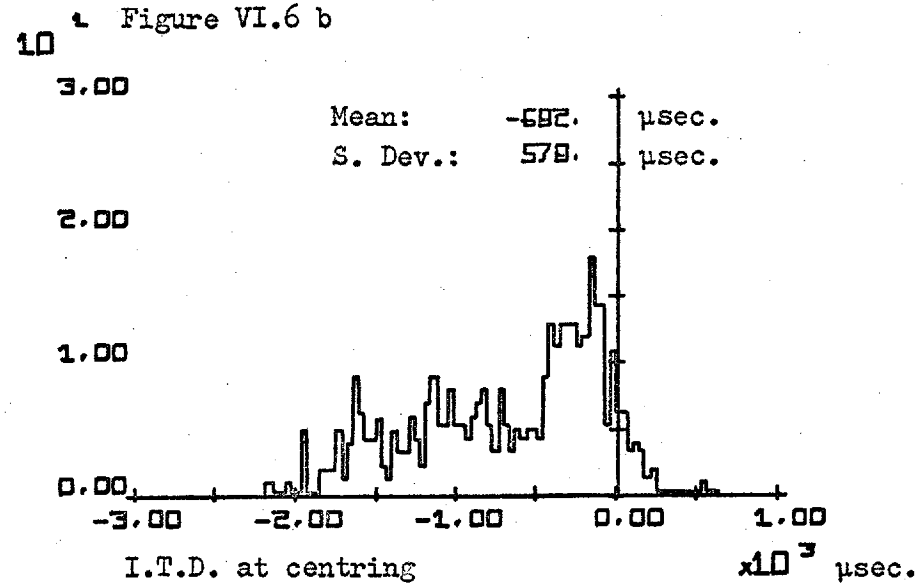


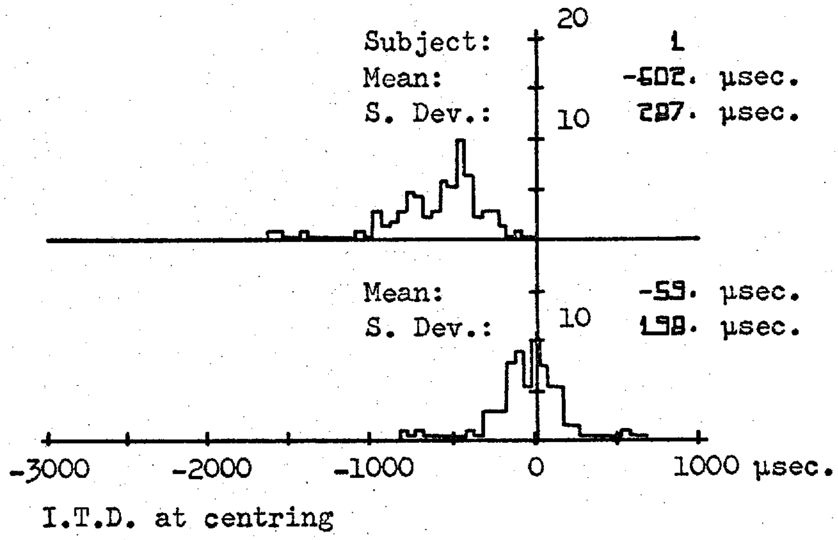
Figure VI.6 c

Figure VI.6 Combined histograms of binaural centrings. Interaction of a pulse with a pulse pair.

Figure a: adapted judgements histogram.

Figure b: unadapted judgement histogram. Pulse pair to the right ear.

Figure c: unadapted judgement histogram. Pulse pair to the left ear



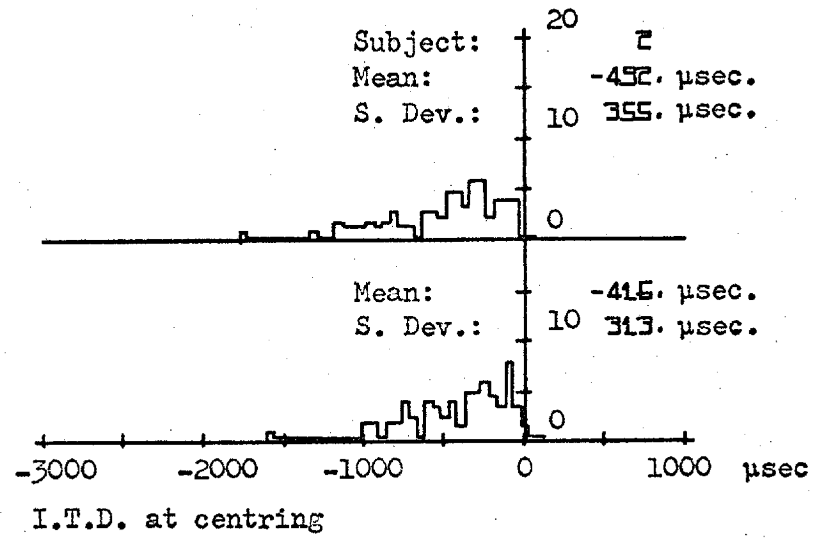
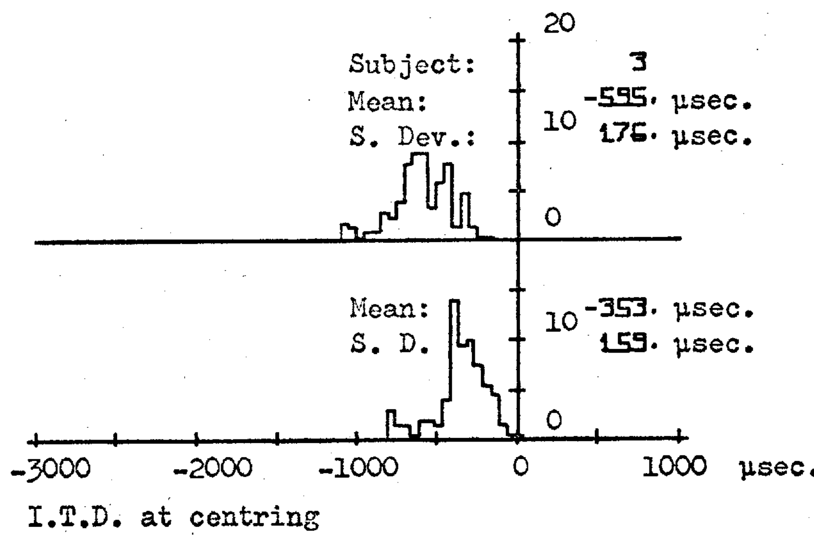
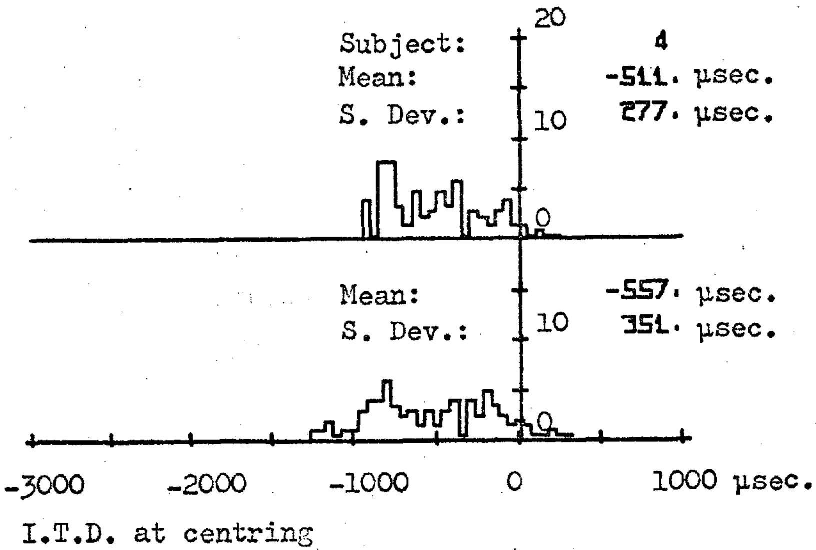
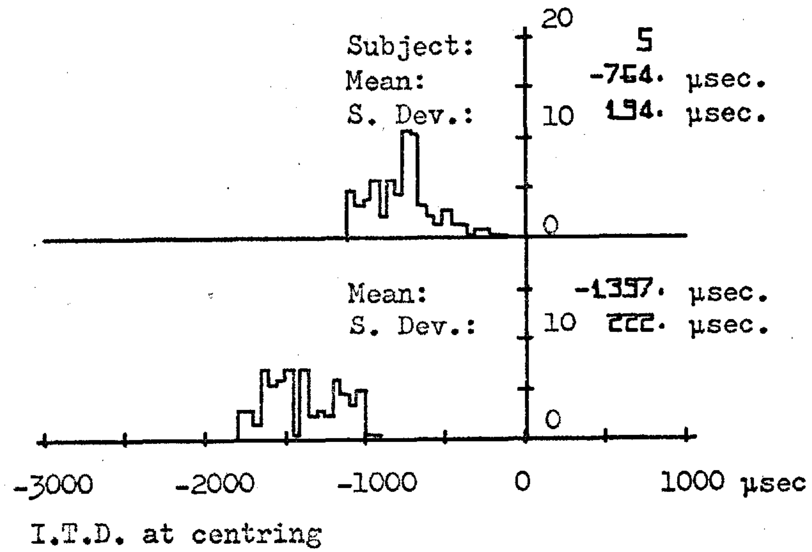


Figure VI.7 a. Individual unadapted judgement histogram. Interaction of a pulse with a pulse pair. The top trace represents the odd numbered judgements.







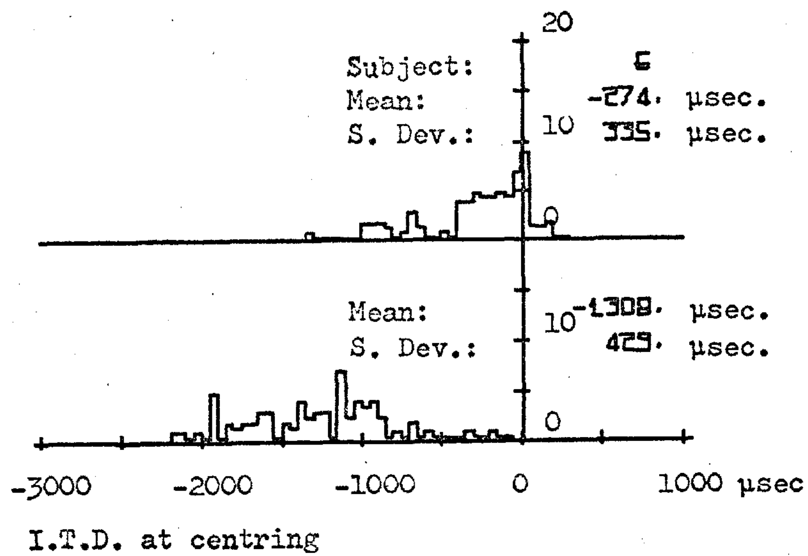


Figure VI.7 b Individual unadapted judgement histogram. Interaction of a pulse with a pulse pair. The top trace represents the odd numbered judgements.

compare the single pulse with the pulse pair neural activity at different place frequencies.

In this particular case it therefore appears that a form of modeling of binaural interaction involving the neural coding of the auditory signal would be most valuable in interpreting the results reported by our experiments. This question is discussed in the section that follows.

VI.5 Modeling the Binaural Interaction of a Pulse with a Pulse Pair.

VI.5.1 Monro's Model: a Representation of the Acoustic Field.

The binaural interaction model proposed by Monro,(1971) essentially provides the type of information that we are seeking; the model has already been discussed in chapter II and we will recall here its main features.

The model uses an analytic expression developed by Flanagan, (1965) to approximate the mechanical displacement of the basilar membrane at various place frequencies. The basilar membrane displacement is then used to control a stochastic process formulated from Gray's detailed analysis (1966) of the probability of firing of auditory neurones; refractory properties are subsequently introduced to generate a probability function that, in the case of an impulsive stimulus, faithfully replicates the previously referred (chapter II) PST histograms reported by Kiang. A binaural interaction mechanism is simulated, that consists of a cross-correlation of the probability functions emanating from corresponding place frequency in the two cochleae.

The result of this operation appears in a three dimensional space: cross-correlation delay vs place frequency vs magnitude of the cross-correlation, for which an appropriate representation is a contour plot.

A binaural simulation of this form has been reported by Monro,(1971), p.233)) for the particular case of the interaction of a pulse with a pulse pair, having the same relative amplitude as we have used in our experiments. Figure VI.8 reproduces the results of the simulation. In this figure the I.T.D. reference is pulse B, while in our experiment it was pulse C.

The important feature that this representation demonstrates is the place frequency dependence of the two dominant images generated by the pulse pair. At place frequency higher that say 800 Hz, the dominant image is created by the interaction of the AB pulses. At lower place frequency, the dominant image results from the AC interaction.

This phenomenon results from a combination of both the mechanical resonances of the basilar membrane and the refractoriness of the auditory fibres. In response to pulse B at 1 Kz place frequency for example, the membrane will have completed two rarefaction cycles before the occurrence of pulse C; the auditory neurones associated with this frequency, are therefore likely to have fired in one of these two rarefaction phases (particularly the second one) in which case they would be in a refractory state when pulse C comes along. Hence pulse C would not generate much neural activity at high frequency places where consequently, no AC image would arise; an AB image would have however already developed.

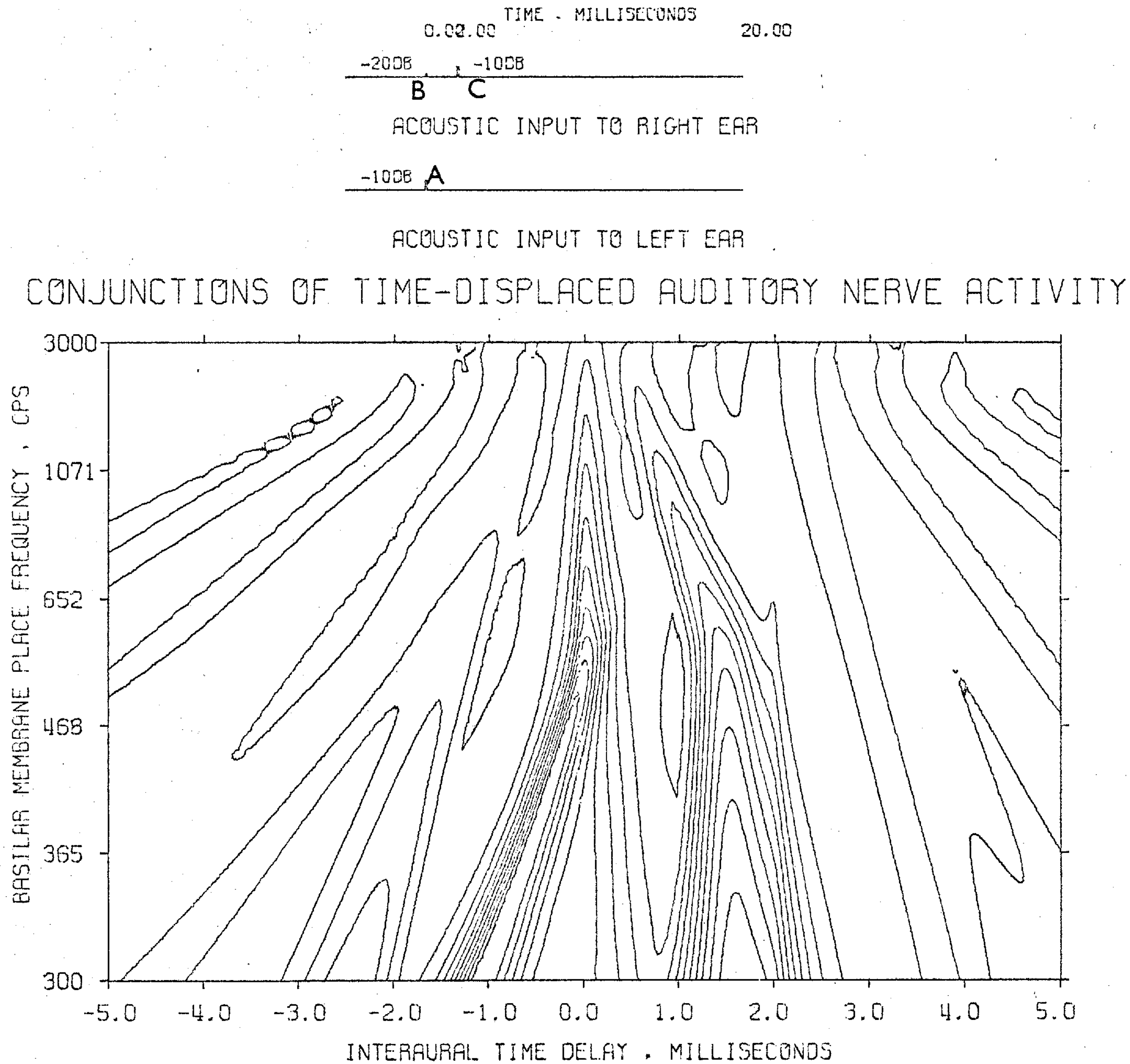


Figure VI.8. Simulated binaural image. From Monro, (1971).

The pulse pair produces a different effect at low frequency places: at 500 hz for instance, pulse B will enhance the second rarefaction phase and its corresponding neural activity; the pulse pair would therefore generate a dominant AC image in the region of low frequency places.

VI.5.2 Interpretation of the Binaural Centring Histograms in Relation to the Acoustic Field Predicted by the Model.

The form of the acoustic field predicted in Monro's model provides a relatively simple explanation for the perceptual behaviour described by the centring judgements histograms.

a) A.C. interaction.

The situation is summarised by saying that the AB and AC images tend to be mutually exclusive in different region of the membrane. In particular, the reported centring of the AC image could be interpreted as attention being paid to the more apical cochlear places (near 300 hz); as already mentioned the AC image there dominates the field.

A strong resemblance between the model's prediction and the experimental results suggests that this was indeed the case. In our experiment the AC image has been reported shifted towards pulse B by some 200 µsec (observation (iii), section VI.4); the model strikingly replicates this situation in the cross-correlation of the apical part of the cochlea, (say 300 hz place frequency): the AC image appears at 1.7 msec, hence shifted 300 µsec towards B.

b) The AB image.

From the model representation it is seen that the AB image dominates in the high frequency region and that in the acoustic field, it is biased towards pulse C; this bias is a result of the 10 db I.A.D. between pulse A and B and therefore produces an image shifted by some 300 μsec towards pulse C. (see the unadapted judgements distribution, in 10 db I.A.D. experiment, figure V.8a). Figure VI.6c shows that this was the case, i.e. a mode is seen in the vicinity of -1700 μsec.

c) Combination image.

Our experiments have reported a type of image that the model does not seem to include, i.e. an image that appears to be a combination of AB and AC images. (observation iv, section VI.4).

Examination of figure VI.6B, where this type of image has been almost exclusively reported, indicates that on the average, it has been centred at -540 μsec I.T.D. It is interesting to note that this position approximates very closely the center of gravity of the pulse pair in figure VI.1, that theoretically, would be at -480 μsec with reference to pulse C.

We believe that this particular image can be accounted for most directly by a peripheral transformation of the acoustic signal. The similarity between the position of the combined image and the position of the centre of gravity of the pulse pair suggests underlying mechanism that performs a running average of the acoustic signal. For all practical purposes, a form of running average can be realised by using a leaky integrator or more simply by low-pass filtering: a function achieved by the basilar membrane at the more apical end (say below 200 hz place frequency.)

Our proposition essentially presents a mechanical averaging process underlying the creation of the combination image. Alternatively, a neural averaging can be envisaged as being at the origin of this phenomenon. In order to explain the I.A.D./I.T.D. effects, Sayers and Lynn,(1968) had proposed a binaural interaction mechanism in which lateralisation judgements were made based on a cross comparison of the center of gravity of the P.S.T. histograms of neural activity, emanating from corresponding cochlear places. Considering a single P.S.T. histogram as the neural response to the pulse pair, the averaging process that explains the I.A.D./I.T.D. effects could again predict the combination image.

This latter proposition however presupposes a linear relationship between the neural response and the individual pulse of the pair, otherwise the centre of gravity of the P.S.T. histogram would not correspond to the centre of gravity of the pulse pair. Goblick and Pfeiffer,(1969) recorded the P.S.T. histogram of cochlear nerve fibres in response to a pulse pair, and found non linearities (now presumed to be due to refractoriness on the occurence of the second pulse) that could not favour the neural averaging alternate proposition.

We therefore propose that the combination image arises from the cross-comparison of the neural activity emanating from the apical part of the cochleae. The results of a comparison of this type will, as we may suppose, duplicate the experimental situation depicted in the centring judgement histogram (figure VI.6b) and consequently explain the shifted position of its center of gravity.

Similarly it also provides explanation for the very large standard deviation of the centrings distribution. The impulsive images emanating from the apical end of the cochleae are necessarily more diffuse than the more basal ones, simply because the peaks of the

PST histograms of the neural activity (of which presumably the binaural interaction mechanism performs the comparison) are wider at the apical end than at the basal end of the cochleae. The image being more spread, quite obviously its binaural centring will be achieved with a larger standard deviation.

d) Adaptation.

From the discussion that we have presented, it now appears that adaptation, in this particular experiment, can be interpreted as a progressive shift of attention from an image to another: a comparison between adapted and unadapted judgement histograms, figure VI.6, justifies this interpretation.

The question of the origin of adaptation has been studied earlier (chapter V, section 5) and our conclusion was that it originated from middle ear muscle activity, controlled by a central mechanism that acted to equalise the intensity perceived by each ear.

We believe that in the interaction of a pulse with a pulse pair, adaptation also originates from this process, i.e. a progressive adjustment of the loudness of the pulse pair versus the loudness of the single pulse.

The question now is how can this intensity adjustment produce a shift of attention from one image to another? The explanation goes as follows. The unadapted judgement histogram* indicate that attention is being paid (according to the above discussion) to the apical end of the cochlea and that image AC is not perceived; at high place frequency (1 kz) this image does not arise, because pulse B has left the auditory neurones in a refractory state when pulse C comes along. However if the pulse pair is attenuated (via the middle ear muscle) then pulse B is not so likely to produce refractoriness; the probability

*Figure VI.6 b.

that pulse C produces firing then will increase and consequently an AC image will now arise at high place frequency. This image, now present along the whole basilar membrane, is more likely to attract attention from the listener and then produce the type of adaptation that we have shown in our experiments.

This situation has been simulated in the digital computer model of Monro; we are most indebted to Dr D. Monro for his permission to use the original program he developed to implement his model.

In the simulation, the relative amplitudes of the A.B.C pulses were made: 0 db, -20 db, -10 db, that is to say the middle ear muscles attenuated the pulse pair by 10 db. This amount of attenuation is suggested by the fact that the pulse pair sounds 5 to 10 db louder than the single pulse.

Figure VI.9 presents the results of this simulation that confirms our theory in a self-explanatory manner.

VI.6 Further Experiments with Multiple Clicks

We have performed a second set of binaural experiments involving the interaction of a pulse with a pulse pair; in this case however the amplitude ratios of the A.B.C pulses were set to 0 db, -5 db, 0 db respectively. These experiments were conducted to investigate how adaptation affects binaural centring of the pulse pair, (shown in figure VI.1) when the level of the A.B image is raised.

Essentially repeating the procedure previously outlined, six subjects contributed to the experiments; set of 128 "adapted"

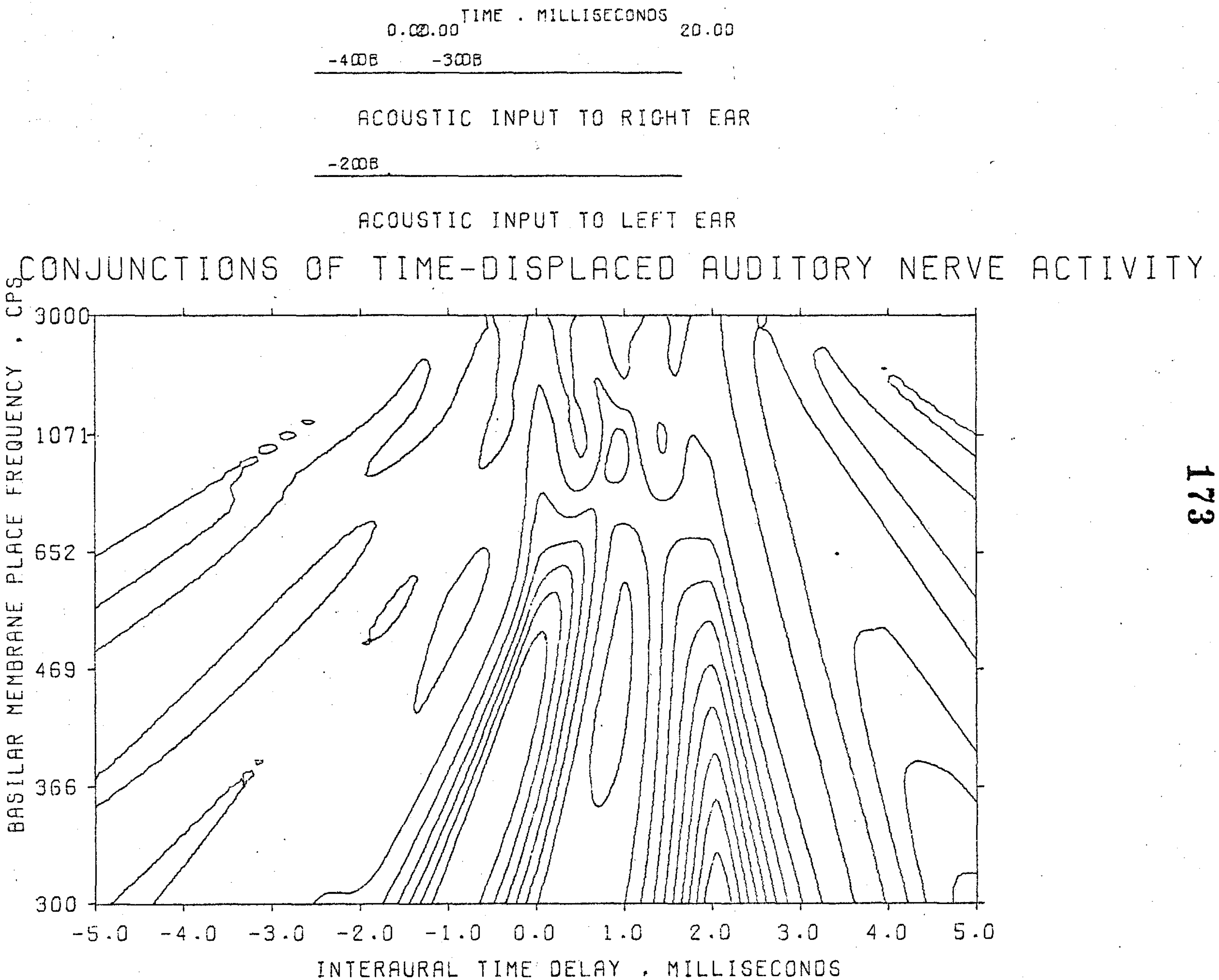


Figure VI.9. Simulated binaural image

and "unadapted"[1] judgements were recorded with each subject.

The results shown in figure VI.10 and VI.11, indicates that, due to the increased level of pulse B, the AC image is not reported consistently. Presumably this arises from the AB image gaining in importance, an effect probably associated with the dominance of the 1 Khz region of the basilar membrane. (where the AB image is formed, according to an earlier discussion).

The sequence of averaged binaural judgements, (figure VI.10b) does not evidence any form of adaptation. However, the effect can be detected in the differences between "adapted" and "unadapted" judgement histograms: although a shift of attention from the AB image to the AC image is not so clearly shown, the increased importance of the AC interaction suggests that the same adaptive mechanism has been involved.

VI.7 Conclusion

The experimental study reported in this chapter shows that repeated presentation of an acoustic stimulus consisting of a pulse vs a pulse pair, is accompanied by changing perceptual behaviour.

The phenomenon is similar to the previously described (chapter V) adaptive process, hence the same underlying mechanism is postulated.

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[1] The terms "adapted and "unadapted" judgements refer here to the experimental technique; adapted judgements were recorded from experiments where the pulse pair was always fed to the right ear; unadapted judgements, where the pulse pair was alternately presented to the right and left ear.

The collection of a large number of binaural judgements (necessitated by the very large standard deviation of the centring judgements produced in these experiments) led to the identification of three distinct acoustic images. Having compared these results with previously reported simulations (Monro,(1971)) of binaural interaction, it was suggested that the images emanated from identifiable place frequencies; accordingly an adaptive process was proposed that consists of a shift of attention from one image to another. It was shown that a middle ear attenuation mechanism could, indirectly, be at the origin of the phenomenon; it is believed that the cause behind the shift of attention is an increase of the probability of firing in response to the second pulse of the pair (pulse C) due to a lowering of the refractoriness related to the occurrence of the first pulse of the pair.

It is important to note however that this effect could arise as a consequence of any form of peripheral attenuation, so it does not rule out the possibility that the inhibitory action of the efferent system may be involved: experiments by Borg,(1971) on un-anaestetised rabbits, have suggested the efferent system acts as a sensitivity control of cochlear activity, providing an attenuation up to 12 db above 500 hz.

The reason why we favour middle ear muscle activity to be at the origin of the adaptive process referred to here, is that physiological recordings have shown that it plays an important role in animal attention and habituation to acoustic stimuli and that it can also be related to the psycho-physical behaviour presented in this chapter; this certainly does not imply that the efferent system is not involved in the process.

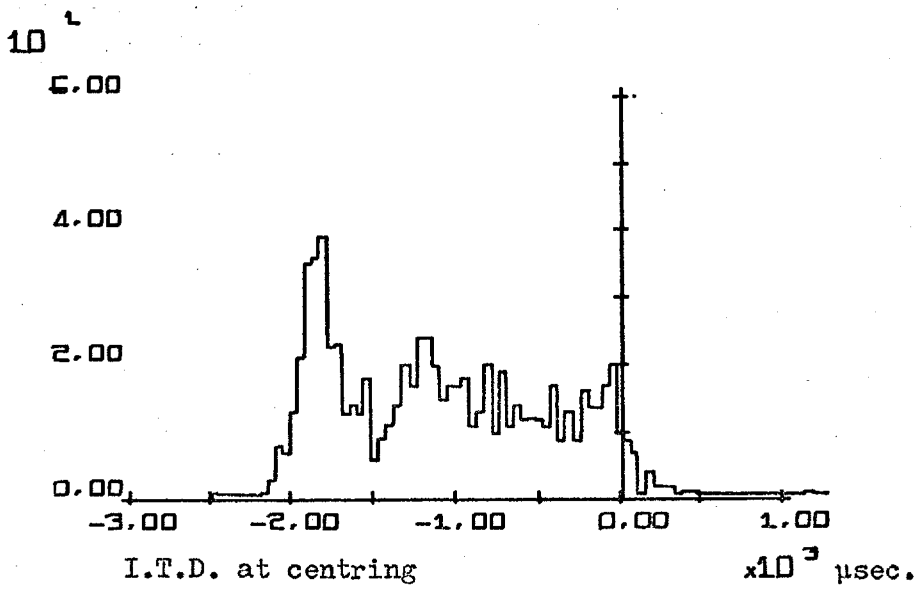


Figure VI.10 a. Combined histogram of centring judgements. Interaction of a pulse with a pulse pair. 6 subjects.

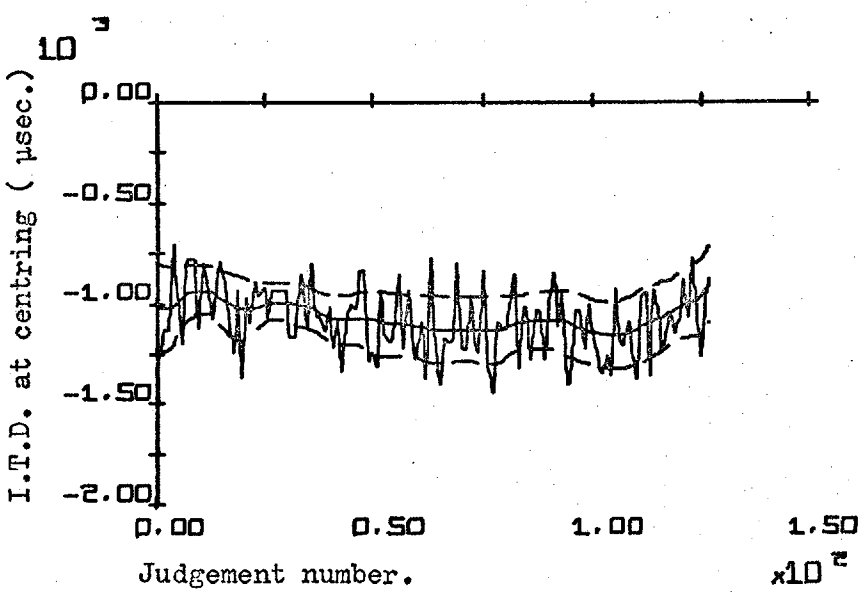


Figure VI.10 b. Averaged sequence of binaural centrings. Interaction of a pulse with a pulse pair. 6 subjects.

Figure VI.11 Combined histogram of unadapted binaural judgements. Interaction of a pulse with a pulse pair.

Figure a: pulse pair presented to the right ear. Odd numbered judgements.

Figure b: pulse pair presented to the left ear. Even numbered judgements.

A:B:C ratios : Odb, -5 db, 0 db.

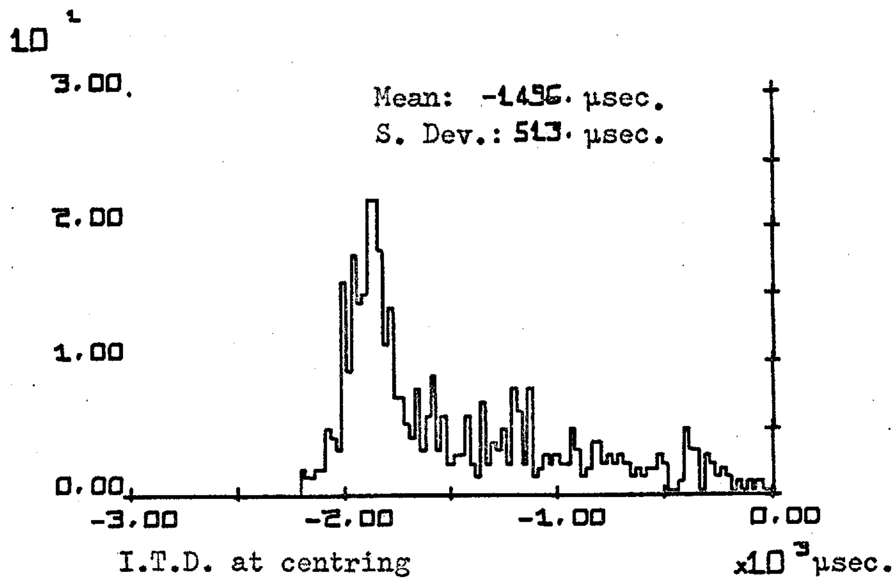


Figure VI.11 a

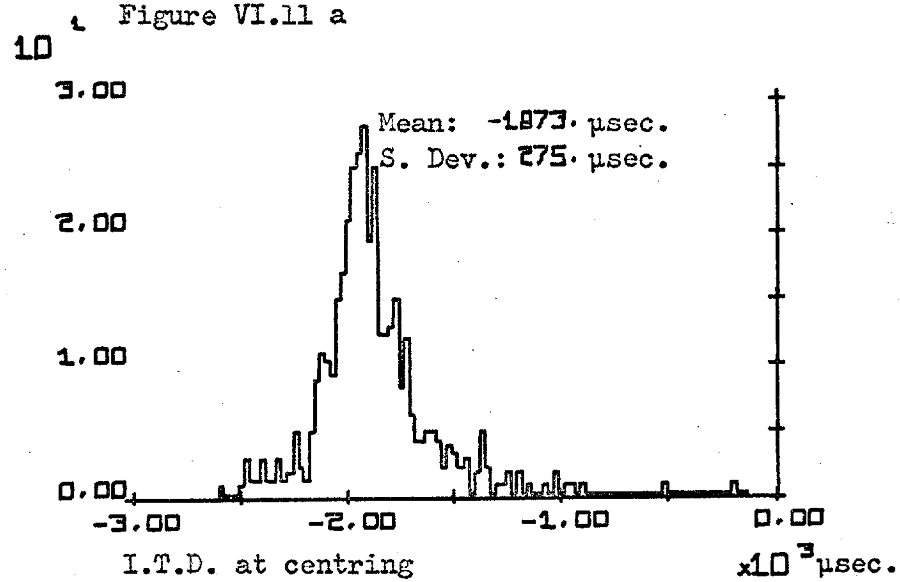


Figure VI.11 b

CHAPTER VII

CONCLUSION

VII.1 Summary and Conclusion

This study has been concerned with two major dynamic aspects of binaural perception. Firstly the human capability of lateralising a moving sound source has been investigated in the particular case of auditory compensation tracking.

The frequency response of a human operator in a compensatory tracking task of this sort has been inferred from the Fourier analysis of the averaged dynamic binaural centrings; these were considered as responses to a step function of inter-aural time delay. It was found that the operator function could be adequately represented by a first order low pass filter with a cut-off frequency of 0.12 hz and cascaded with a pure delay of 0.6 sec.

The second dynamic aspect of binaural perception to which this study related was concerned with the perceptual changes associated with repeated presentations of acoustic stimuli. As a general rule it was found that binaurally unbalanced signals caused, on a long term basis, significant changes to successive binaural centring judgements.

The phenomenon, labelled binaural adaptation, was investigated in the interaction of simple and complex transients. Examination of some of the possible causes of binaural adaptation led to the conclusion that centrally mediated middle ear muscular activity was the most likely origin of the phenomenon; the possibility that the efferent system may however play an important role in this particular dynamic matter must be left open till binaural measurements of middle ear impedance are made.

Paralleling this study we presented some experimental verifications of certain psycho-physical behaviour predicted by a recently formulated model of binaural fusion. In particular we were concerned with the problems related to the perception of co-existing multiple images that arise from peripheral transformations imposed on the acoustic signal.

In the case of interaction of simple auditory transients with inter-aural amplitude difference, the existence of such images was demonstrated. With a large value of amplitude difference (20 db I.A.D.) three images were identified as occurring at regular intervals of inter-aural time difference. (800 µsec.) These findings would be in accordance with the modified cross-correlation theory of binaural fusion where binaural interaction results from cross-comparing the neural activity emanating from corresponding cochlear places. In particular the correlation-time spacing of the images suggested that the 1.2 hz region of the basilar membrane had been chosen to perform the cross-comparison; indeed this region of the membrane had already been found to be dominant in binaural perception.

With a smaller value of inter-aural amplitude difference (10 db I.A.D.) the existence of coexisting images was more difficult to demonstrate and without amplitude difference (I.A.D. 0 db) no secondary image could be detected.

In the case of the interaction of more complex auditory transients (double versus single click interaction) three distinct images were identified. The model's representation of the acoustic field suggested that these images arose from identifiable basilar membrane place frequencies and resulted from the complex, but predictable, peripheral neural coding of the acoustic stimuli.

This experimental investigation on the perception of multiple images does permit a further insight into the problem of auditory attention and habituation. In particular the interesting finding has been such that in both simple and complex transient interaction, adaptation could be related to the perception of multiple images and could be interpreted as a progressive shift of attention from one image to another. In the case of the interaction of complex transients, this important dynamic aspect could be explained in terms of a peripheral attenuation mechanism such as provided by the middle ear muscles.

Essentially this work stresses the importance of studying the perceptual changes associated with the repeated presentation of acoustic stimuli. It underlines that the notion of trained and untrained subjects needs to be applied with care: in some cases it may lead to an oversimplified picture of a particular type of binaural interaction. Indeed the first 10-15 presentations of acoustic images could have been treated as training stimuli and subsequently rejected: quite certainly an important point would then have been missed.

VII.2 Proposals for Further Research

As frequently mentioned in the course of this work, further binaural listening experiments should be carried out with the middle ear muscle activity simultaneously monitored in both ears. Such measurements would indeed be most valuable in many respects: the ear muscles' contribution to binaural adaptation and more importantly their exact role in auditory attention and discrimination could be assessed. In centring experiments where competing acoustic images are presented, a correlation between the muscles' activity and the corresponding binaural judgement should provide the necessary elements to shed some light onto this problem.

A possible technique to measure the middle ear activity in the course of a binaural experiment, would be to record the acoustic impulse reflected in the auditory meatus from the tympanic membrane. This could be done by inserting in the meatus two small tubes respectively acting as transmitter and receiver tube. The reflected pulses could then be digitised and subsequently averaged to improve the signal-to-noise ratio of the signal. A Fourier analysis of this averaged impulse (amplitude spectrum) should give an idea of the mechanical impedance changes that happen in the course of the experiments.

Further listening experiments should be carried out to study the effect of the level of the acoustic stimuli (relative to the threshold of hearing) in relation to adaptation and auditory attention. At low level (say below 40 db re .0002 dynes/cm^2) the effect of the middle ear muscles should be less important since, presumably, the acoustic reflex would not arise in such circumstances. Obviously these experiments would need to be done in an environment where the ambient noise is very low, such as certain types of anechoic rooms.

The question of binaural adaptation should be further investigated to evaluate the time course of the associated recovery. This could be done using the technique that we have developed to obtain sequence of un-adapted binaural judgements, only interchanging the acoustic input to the headphones at every 20 judgements.

Further psycho-physical measurements should be carried out to study the effect of certain psychological states (motivation, stress, etc.) on binaural adaptation. This particular research is suggested by the fact that we have noted that the same subjects would repeat the same experiment on a different day and produce a different time course of adaptation. This may again shed some light on the role of central mechanisms in auditory habituation.

APPENDIX A

INSTRUMENTATION

This appendix details the design of two instruments specifically built for the purpose of binaural experimentation. As mentioned earlier (Chapter III section 2), these consist of an audio mixer and buffer amplifier, and of a binaural pulse generator. The details presented here are of a technical kind and are given to facilitate eventual modifications or servicing, should this ever become necessary.

A.1 Stereo Mixer and Buffer Amplifier

i) Stereo Mixer.

This apparatus was constructed to generate complex pulse patterns (for example trains of double or triple pulses) using a combination of simple pulse generators.

Each channel is capable of mixing five inputs; the output provides the inverted algebraic sum of the various inputs. The output impedance was fixed at 600Ω to enable a direct connection to the variable filter (type Allison Laboratories, AL2B) and attenuator (Solatron, AT201). The frequency compensation network was chosen to achieve a high slew rate.

ii) Stereo Buffer Amplifier.

This apparatus was built to achieve an impedance conversion from the attenuator (600Ω) to the headphones (8Ω). The gain of the buffer is - 1.

The specifications for this instrument are given in table 1; the circuit is shown in figure A.1.

Supply: $\pm$ 14 Volts

a) mixer:

input: Five inputs per channel
10 K impedance
Fully protected
Dynamic range: algebraic sum of input voltages cannot exceed $\pm$ 6 volts

output: 600 ohms impedance
Short-circuit protected
Bandwidth: 1.5 v/μsec

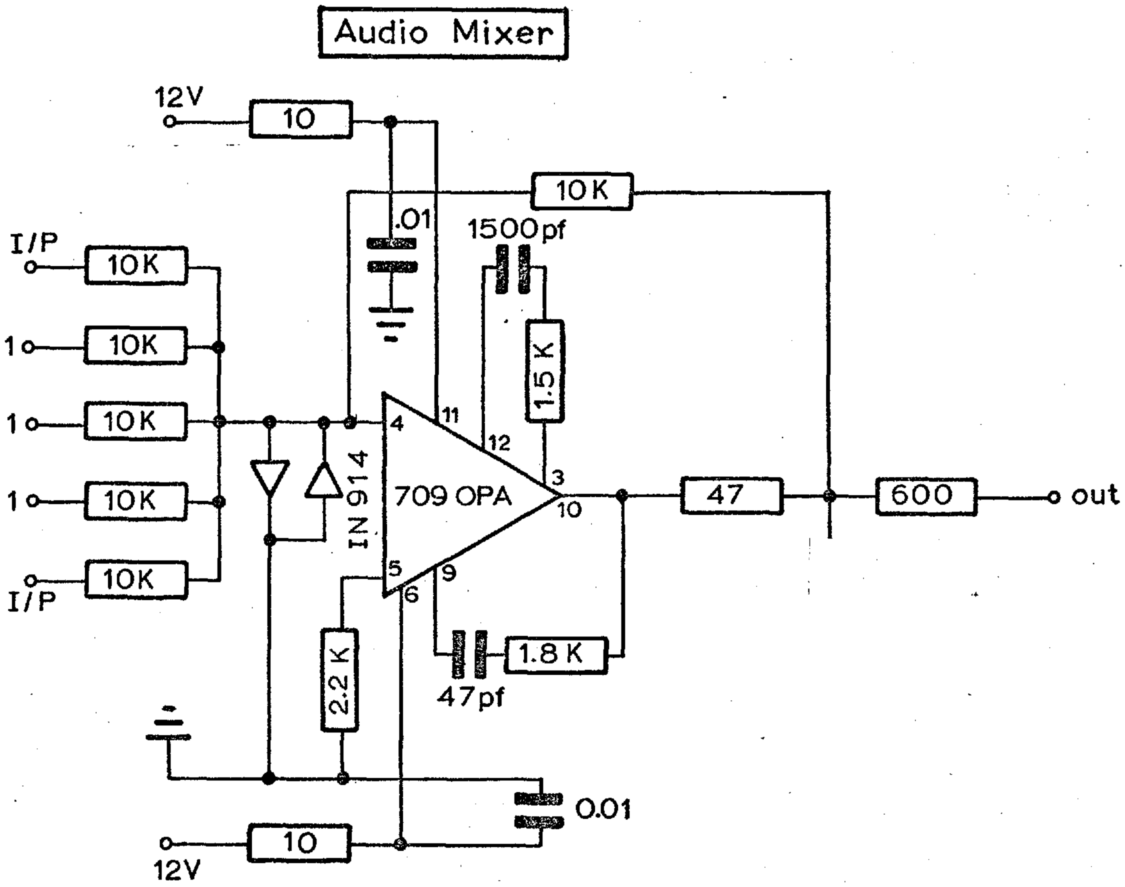
Gain: approx. (-1) $\pm$ 3%
Offset voltage: 13 mv max.
Noise: < 1 mv rms (0 - 15 kc)

b) buffer

input: Impedance 12 K
Fully protected
Dynamic range: $\pm$ 8 volts

output: Impedance less than .5 ohms, max. 5 ma.
Gain: approx. (-1)
Offset voltage 5 mv max.
Noise: < 1 mv rms (0 - 15 kc)
Monitor output for scope: 2.2k impedance

Table 1. Technical specifications of the stereo mixer and the buffer amplifier.



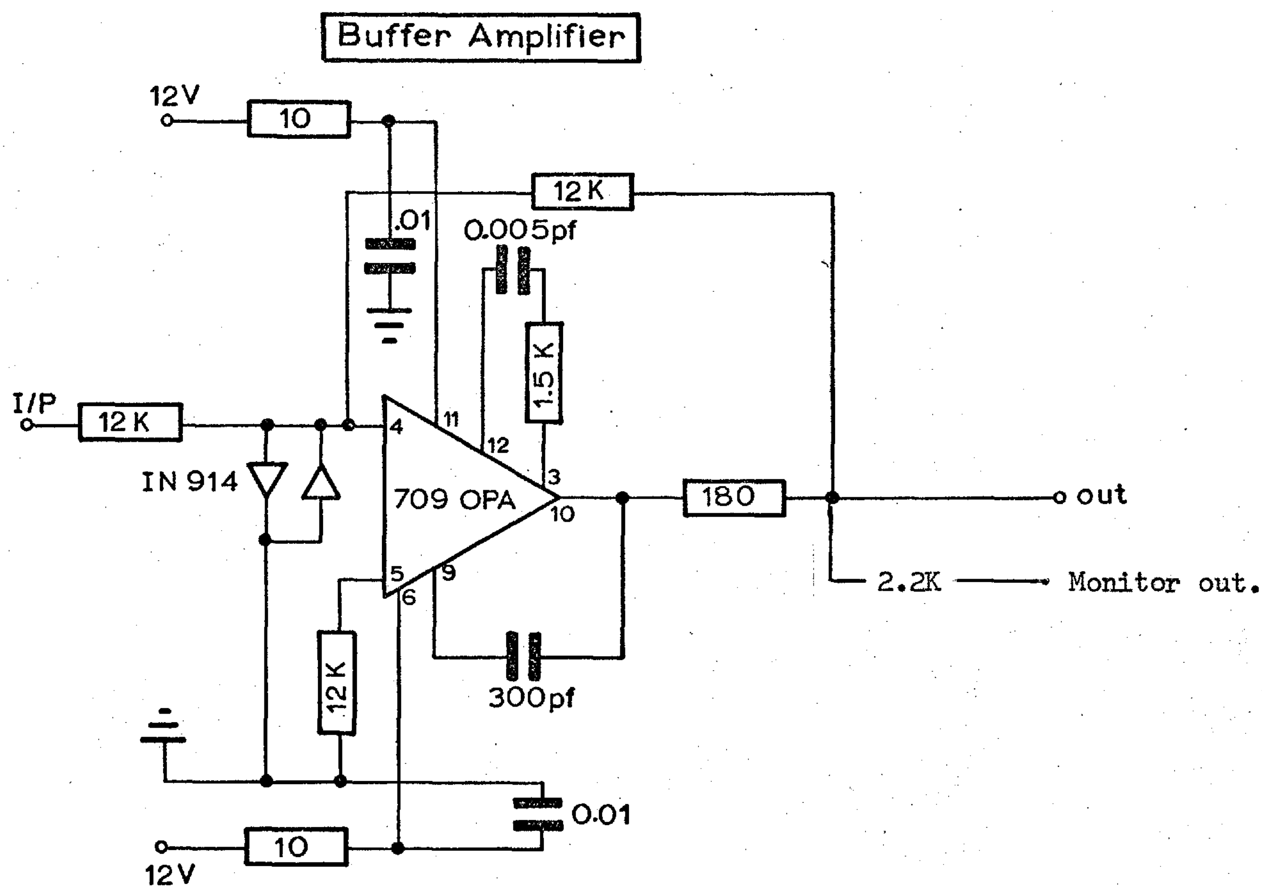


Fig. A.1. Audio Mixer, Buffer Amplifier Circuit Diagram

1-	no. 1 buffer input
2-	no. 1 mixer output
3-	no. 1 buffer output
4-	NC
5-	no. 1 Ground
6-	no. 1 mixer input
7-	no. 1 mixer input
8-	no. 1 mixer input
9-	no. 1 mixer input
10	no. 1 mixer input
11	+ 14 volts supply
12	- 14 volts supply
13	no. 1 mixer monitor
14	no. 2 mixer monitor
15	no. 2 buffer input
16	no. 2 mixer output
17	no. 2 buffer output
18	NC
19	no. 2 Ground
20	no. 2 mixer input
21	no. 2 mixer input
22	no. 2 mixer input
23	no. 2 mixer input
24	no. 2 mixer input

Table 2. Stereo mixer: socket diagram

A.2 Binaural Pulse Generators

A.2.1 General Description

This instrument was specifically designed for binaural experiments involved with the interaction of auditory transients; consequently it possesses certain features that are not common to commercially available units of a similar kind, although the electronic circuitry uses standard techniques.

The apparatus is diagrammatically represented in figure A.2; it consists of five independent pulse generator modules, and a clock unit module. Each generator has three independently buffered pulse outputs: one of these produces a pulse of variable amplitude and switchable polarity; the two other outputs of fixed amplitude provide + and - pulses simultaneously, and are intended to be used as trigger sources for any other pulse generator module.

The fixed amplitude outputs of every unit have been grouped on a single patch board: if this trigger mode is selected, only short lead connections are necessary to trigger any unit from any other unit; with each generator, a switch selects the triggering source either as being the clock unit or its 1 mm socket on the patch board.

Great care has been taken at the design stage to ensure that the generators would not interfere with each other in the timing functions or even in the shape of the pulses themselves. As a general rule, the instrument was designed to provide noise-free, stable delayed pulses.

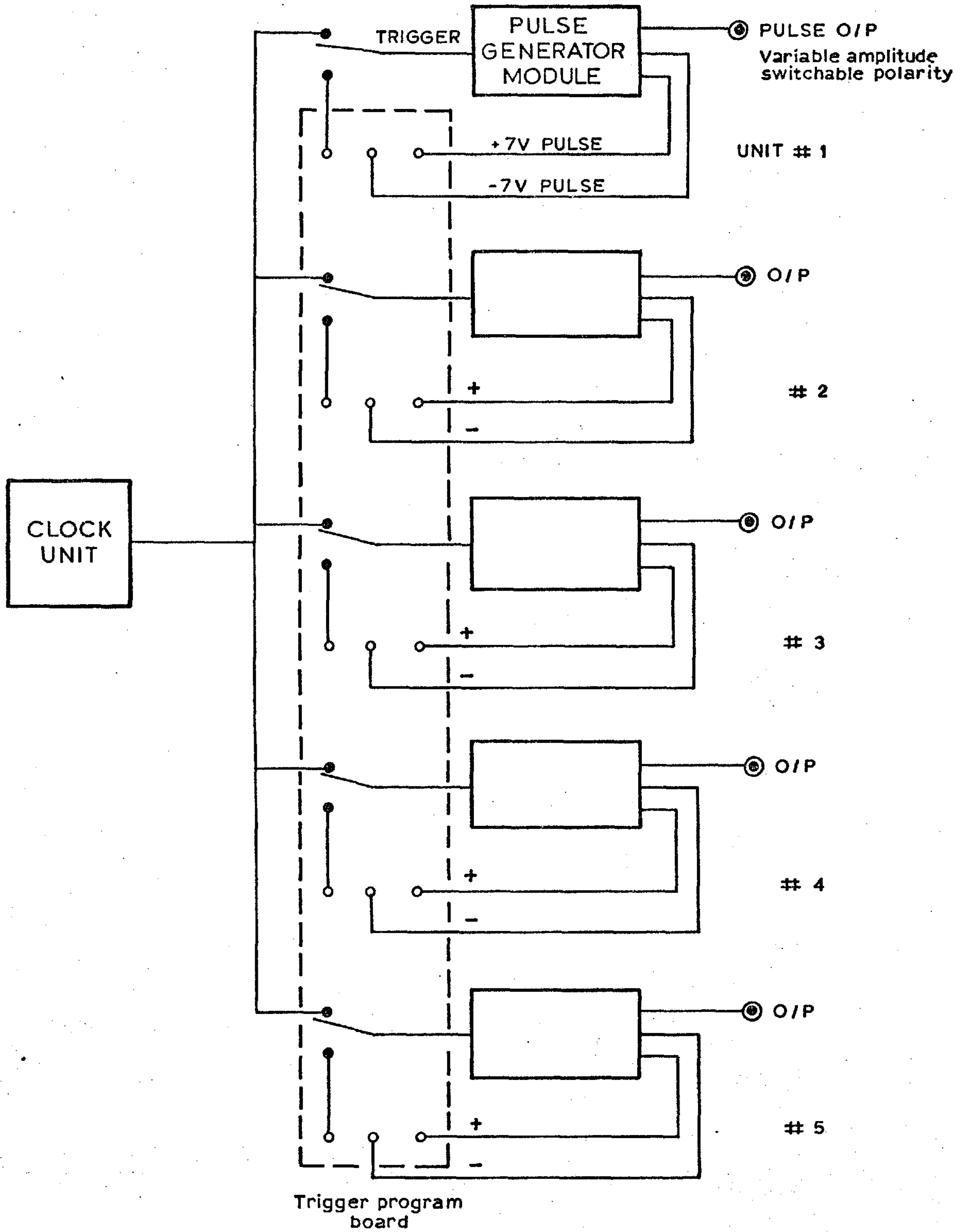


Fig. A.2. Block diagram of the binaural pulse generator

A.2.2 Specifications and Controls

A) Pulse Generator Module. (figure A.4, A.5)

Trigger source:
- Switchable a) clock unit
  b) trigger programme; in this mode, the generator triggers on the positive edge of a pulse coming from any other pulse generator module.

Delay:
- Switchable on/off
- Range: continuously variable from 1 μsec to 100 msec. in 5 decade ranges, with graduated fine vernier control. (10 turn potentiometer)
- Accuracy of the graduation: better than 0.5 % of full range. (in a given decade)
- Stability: after a warm up period of 30 minutes, the delay will drift at a rate < 0.2 %/hour.
- Jitter: less than 2 μsec for a delay of 50 msec.

Programmed delay:
- An external voltage source can be used to modulate the delay of units 1, 2, 3.
- External voltage range: 2 to 5 volts. The instrument is protected, if this range is exceeded, via an electronic fuse. To reset: disconnect the external voltage source, and reconnect a source in the appropriate range.
- Linearity of the variation of the delay: better than 0.3 %

Delay duty cycle:
- Defined as the ratio of delay/repetition period: 80% for .1% variation of delay
  90% for .2% variation
  96% for .5% variation

Pulse width:
- Range: continuously variable from 1 μsec to 100 msec. in 5 decade ranges with graduated vernier control.

(pulse generator module continued)

Output:	. Three separately buffered outputs
	. Trigger Program output: + 7V, -7V nominal
	. Pulse output: switchable polarity adjustable amplitude (0-6V) impedance: 120 Ω .

B) Clock Unit. (figure A.3)

Period range:	. Continuously variable from 1 μsec to 100 msec in 5 decade ranges.
Mode of operation:	. a) continuous by internal clock generator b) single by manual push-button c) single by external trigger signal.
Output:(prepulse)	. Pulse level: 8 V width: 500 nsec.
	. Impedance: 1 kΩ
Trigger input:	. Frequency up to 1 Mhz.
	. Polarity switchable: positive going I/P negative going I/P
	. Impedance: 1 MΩ
	. Level: adjustable -5V to +5V.

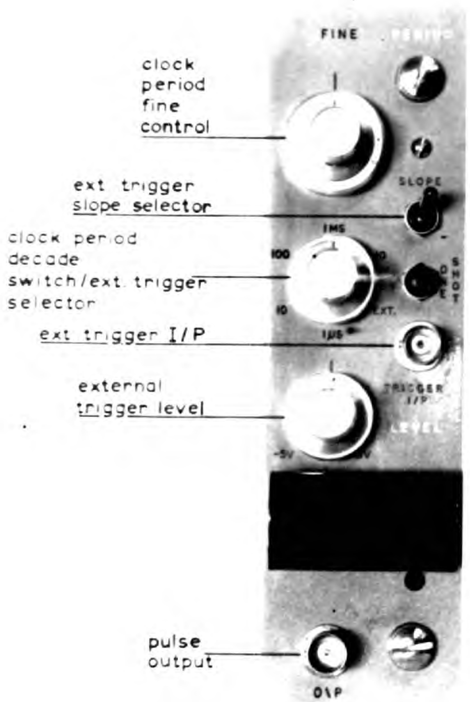


Fig. A.3 Clock Unit Module.

Fig. A.4. Pulse Generator Module.

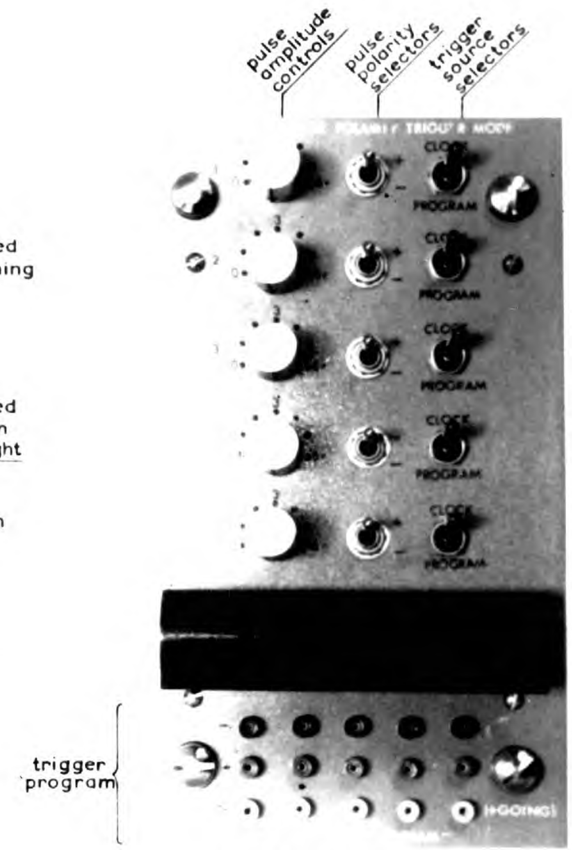


Fig. A.5. Buffers Module.

Controls Identification

A.2.3 Operating Instructions: Checking Operation.

The main switch is on the left hand side, on the front of the instrument; an amber neon indicates the ON state.

A) Clock period:

Set the clock (figure A.3) to obtain a 50 msec period:
- clock period fine control to "5"
- clock period decade switch to 10 msec.

B) Pulse width (figure A.4):

Obtain a 5 msec pulse on every unit:
- set the delay switch OFF. (down)
- set the 1 msec pulse width decade selector ON (up)
  Note: all other p.w. decade selectors must be down, otherwise the appropriate "uncal" light will come on, indicating that the pulse width vernier is uncalibrated.
- set the pulse width vernier to "5".

C) Amplitude, polarity and trigger source. (figure A.5):

- set all trigger source selectors to "CLOCK" (up)
- set the pulse polarity selectors to + (up)
- set the pulse amplitude controls to 3V. (mid position)
  Note: on the buffer module (figure A.5) the top row of controls affects the amplitude, polarity and trigger source of unit 1, the second row of unit 2 etc. In the instrument unit 1, is the leftmost pulse generator module, next to the clock module.

D) Delay (figure A.4):

To obtain a 15 msec delay, on all units:
- set the delay switch "ON" (up)
- set ON (up) the 10 msec delay decade selector, all other delay decade selectors off (down) otherwise the appropriate "uncal" light will come"ON", indicating the delay vernier is uncalibrated.
- set the delay vernier to 1.50
  Note: if at this stage units 1, 2 or 3 do not output any pulse, (when the delay switch is ON), this would

(operating instructions, continued)

be due to the fact that the unit concerned is switched on the "programmable delay mode"; to reset to "normal delay mode", pull out the module (2 screws) and set down the two switches soldered onto the printed circuit. (veroboard)

E) Single (one shot) mode:

- set the clock period decade switch (figure A.3) to EXT.
- press the "ONE-SHOT" push button.

F) External Trigger:

- set the clock period decade switch (figure A.3) to EXT.
- connect the trigger source to B.N.C. connector Trigger I/P.
- select trigger slope
- set trigger level.

G) Triggering a unit from another unit:

Say it is desired to trigger unit 2 from unit 5

- set unit 2 trigger selector (figure A.5) to PROGRAM (down)
- using the provided 1 mm lead, connect on the trigger program board (figure A.5) the output pulse of unit 5 (last red socket on right) to the input of unit 2 (white socket, second from left)

Note 1: in this mode, unit 2 will trigger on the leading edge of unit 5. Changing the position of the pulse polarity selector (figure A.5) or the pulse amplitude control of unit 5 does not affect the triggering.

Note 2: to trigger unit 2 from the trailing edge of unit 5, connect (on the trigger program) the negative going output pulse of unit 5, (last blue socket on the right) to the input of unit 2, (white socket , second from left).

H) Programmable delay:

This facility results from a modification of the original design and was intended to enable the analog output of the I.B.M. 1800 computer to control the delay of a pulse generator. The modification has been made with units 1, 2, 3 only.
Three pairs of 4 mm sockets, provided at the back of the instrument, connect the control voltage to the corresponding pulse generator unit.
A unit is set in the "Programmable delay mode" via two miniature switches soldered to the printed circuit of the module. The programmable mode is when these switches are up. See section A.2.2, on Programmed Delay, for the remarks concerning the protection against excessive control voltage.

A.2.4 Principle of Operation (circuit description): Pulse Generator Unit.

A) Block Diagram (figure A.6/A.7)

The block diagram shows that the system is functionally divided in three parts: a delay, a pulse width and a buffer stage. The first two essentially achieve timing function and, using relatively little current, enable effective decoupling and so minimize interference with other timing units. The third stage, (buffer stage), produces the pulse output and consequently generates much higher current transients; the effects of those transients on the timing stages are however minimal, since the buffer relates to the delay and pulse width stage only via low level set and reset connections.

The following description should be read along with figure A.7 that shows the relative timing of signals at various labelled points.

To output a delayed pulse, the system works as follows: (SW 1 in "DELAY ON" position).

A differentiated trigger pulse, differentiated so as to pick up the positive going edge only, set the bistable (FF1) to the logical "1" state. ($\overline{Q}$ = 0). RG1 is then switched ON (via ES1), and consequently generates a voltage ramp at point No.4; this voltage rises until it reaches the level of the reference voltage, at which point the comparator (C1) outputs a pulse at point no.5. This pulse resets FF1 (logical "O" state, $\overline{Q}$ = 1) that in turn switches OFF the ramp generator. The comparator pulse, point no.5, can be seen as a delayed version of the trigger pulse.

The comparator pulse (point no.5) now sets on the pulse width function by providing a set pulse at bistable FF2; this switches on the ramp generator and, as with the delay function, a reset pulse will

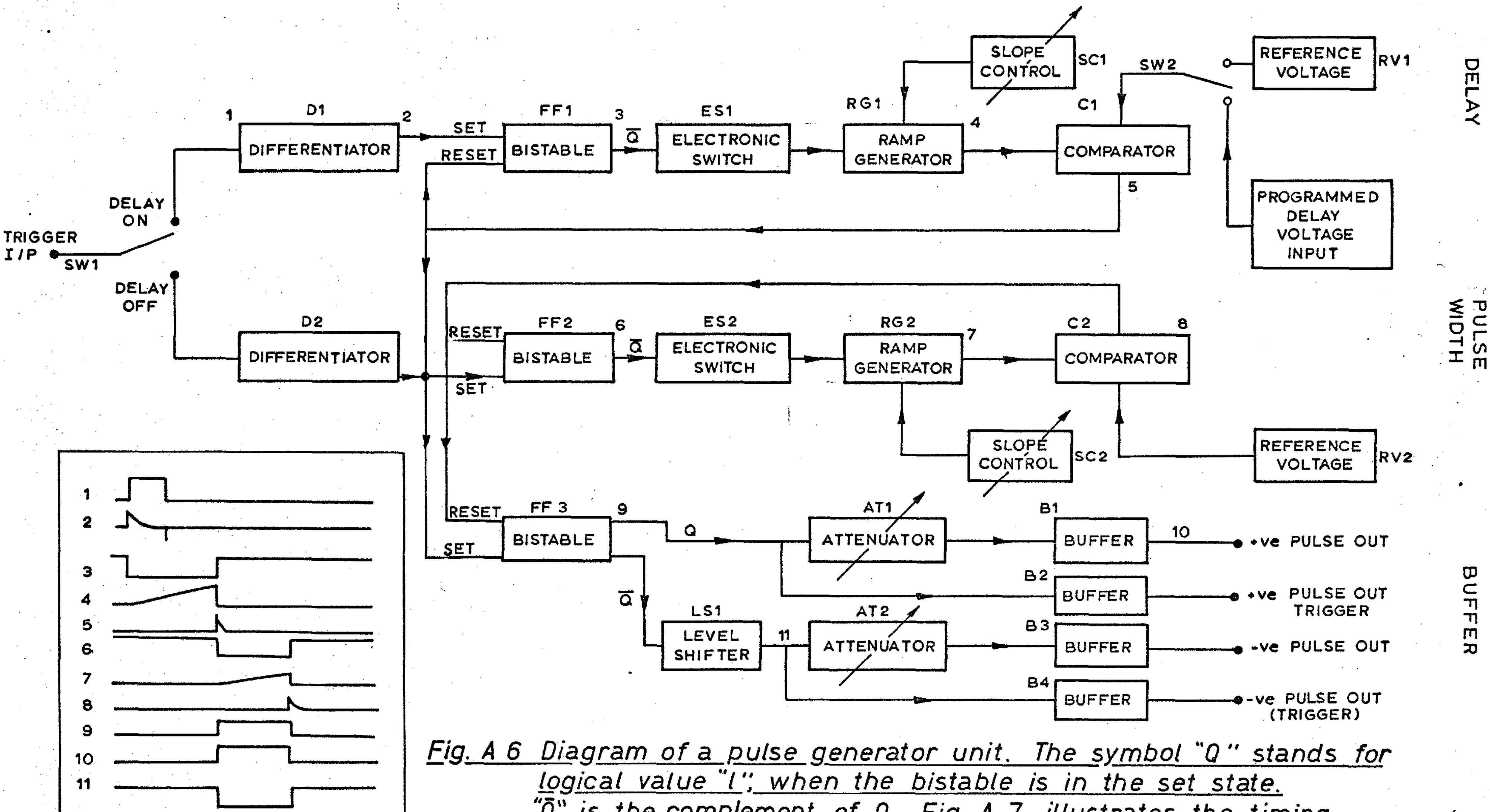


Fig. A.7.

Fig. A 6 Diagram of a pulse generator unit. The symbol "Q" stands for logical value "1", when the bistable is in the set state. "Q̄" is the complement of Q. Fig. A.7. illustrates the timing sequence of the labelled output.

output from comparator C2 (point no.8), eventually switching OFF the ramp generator. The time interval between the set and the reset pulse of bistable FF2, corresponds to the desired pulse width.

It is seen that the output of FF2 (point no.6) is in fact a delayed square pulse that could be used as the output of the pulse generator itself. However, it was found desirable to separate the timing functions (delay and pulse width) from the pulse output function, in order to achieve very stable delay, irrespective of the load at the buffer stage.

For that purpose, the set and reset inputs of bistable FF3 are connected in parallel to the set and reset inputs of FF2: therefore FF3 produces the same pulses as FF2. Practically, interference between the timing and buffering function was kept low by using separate supply for FF3 and (FF1 - FF2).

From figure A.7, it is seen that the Q output of FF3 produces the positive pulse; the $\bar{Q}$ output, after a shift of the D.C level, produces a negative pulse (point no.11)

On the instrument, the delay and pulse width functions make the pulse generator module; the buffer stages of every unit have been grouped on a single module and make the Buffer module (figure A.5).

B) Electronic Switch, Ramp Generator, Comparator and "Uncal" Indication. (Figure A.8)

The description presented here, refers to the delay function but because of the similarity, applies to the pulse width function.

i) Electronic Switch.

The elctronic switch (ES 1, figure A.6) consists of transistor T_1, connected in the reverse mode to achieve lower saturation characteristic.

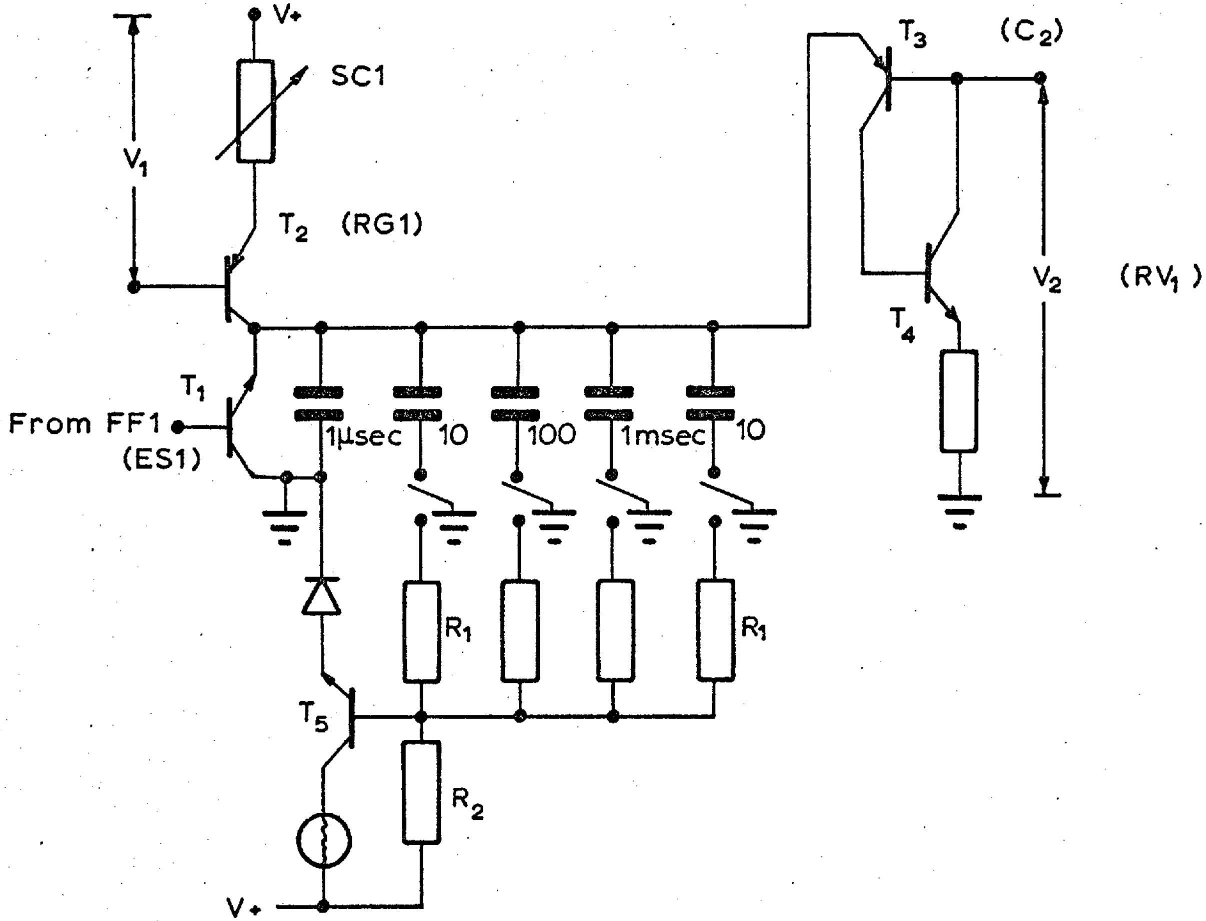


Fig. A.8. (See text)

When FF1 is reset, $\overline{Q} = 1$, hence T_1 is saturated and short-circuits to earth the timing capacitors. When FF1 is set, $\overline{Q} = 0$, and the base of T_1 is driven to ground so the timing capacitor charges.

ii) Ramp Generator.

The ramp generator is simply a capacitor charged by a current source; the current source is constituted by T_2; the base of T_2 is kept at a constant voltage V_1, hence the voltage across the T_2 emiter resistor is also kept constant; because T_2 is a high gain transistor its emiter current nearly equals its collector current which is therefore controlled by the emiter resistor. (SC1)

iii) Comparator.

The comparator is constituted by a pair of PNP-NPN transistors; T_3 and T_4 are normally kept OFF; when the emiter voltage of T_3 reaches the base voltage (of T_3), current flows through its collector hence through the base of T_4. This current is amplified by T_4 and consequently the base voltage of T_3 decreases further to initiate the regenerative discharge process.

iv) "Uncal" Indicator.

The decade selection is achieved by connecting capacitors in parallel to T_1; single pole change-over switches are used for that purpose. With this technique, there is a risk that more than one switch may be connecting in parallel more than one capacitor hence decalibrating the time base. Therefore a warning "uncal" signal system has been incorporated; this warning system consists of R_1's, and R_2 resistors, a transistor and a filament bulb. R_1 and R_2 make a potential divider so that if more than one R_1 resistor is disconnected from earth (i.e. more than one capacitor is switched to earth) then T_5 conducts and the bulb switches ON.

A.2.5 Principle of Operation (circuit description):Clock Unit.

Figure A.9 gives the block diagram of the clock unit, relating more specifically to the External Trigger mode facility of the module.

It is assumed that when the external trigger signal is smaller than the reference voltage, the comparator is in the "0" state, and that the 500 ns monostable responds only to a change from "0" to "1".

When the external trigger signal becomes greater than the reference, the comparator output goes from "0" to "1". If the external trigger mode of the clock unit has been selected, (frequency selector to: Ext. Trig.), the disabling gate is inoperative, therefore the output of the comparator is fed directly to Inverter 2; inverter 2 enables to select a negative slope ("1" to "0") to trigger the monostable.

When the External Trigger mode is selected, the time base is made to behave like a .4 seconds monostable to provide a "One Shot" facility.

Figure A.10 gives the block diagram of the time base; it resembles in many ways the previously described delay and pulse width functions. In short it could be seen as two delayed pulse generators triggering each others.

Assume the bistable in the reset state; then $Q = 0$, $\overline{Q} = 1$; hence RG_3 produces a ramp that will eventuate in C_3 producing a set

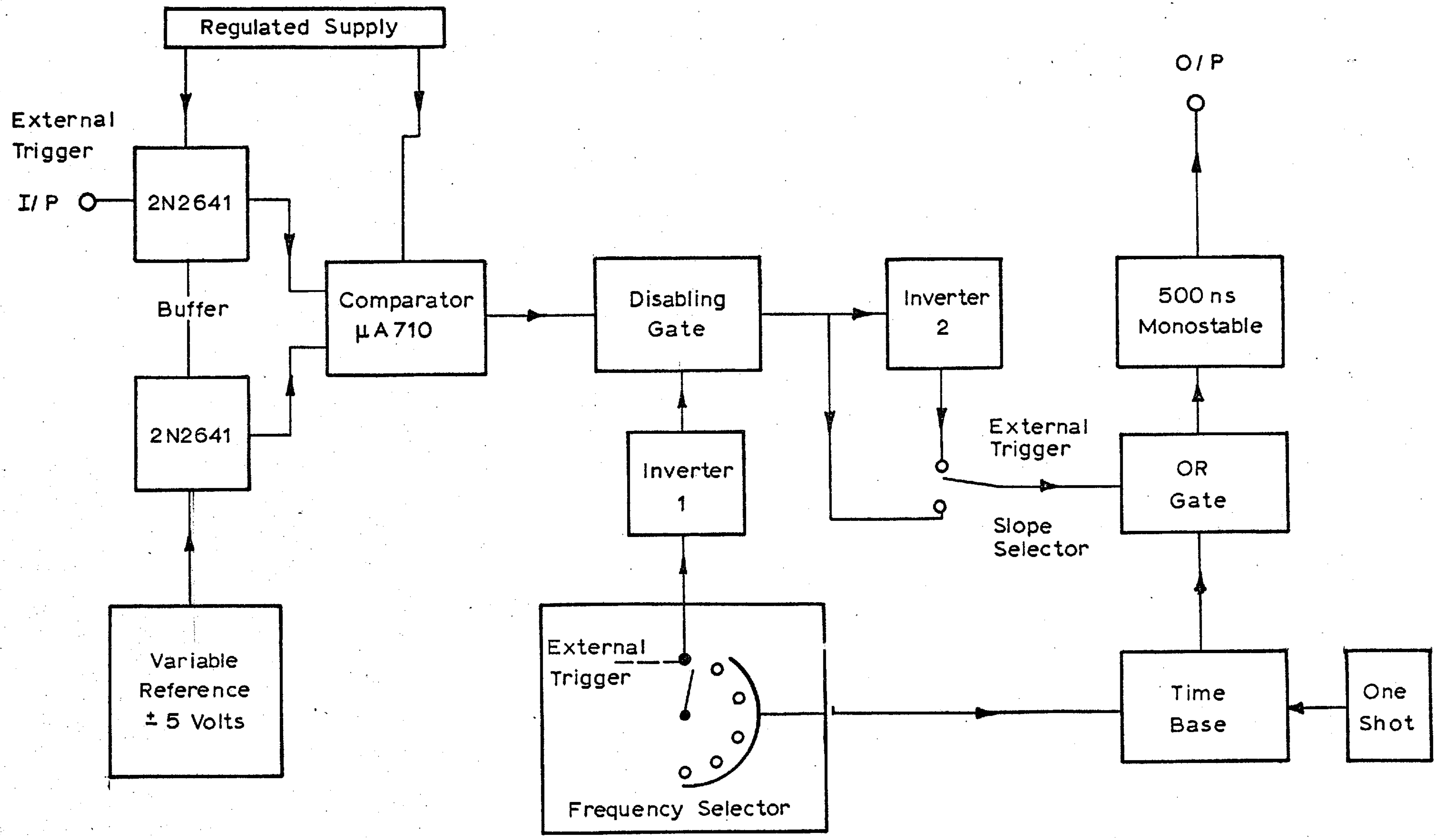


Fig. A.9. Clock unit : block diagram.

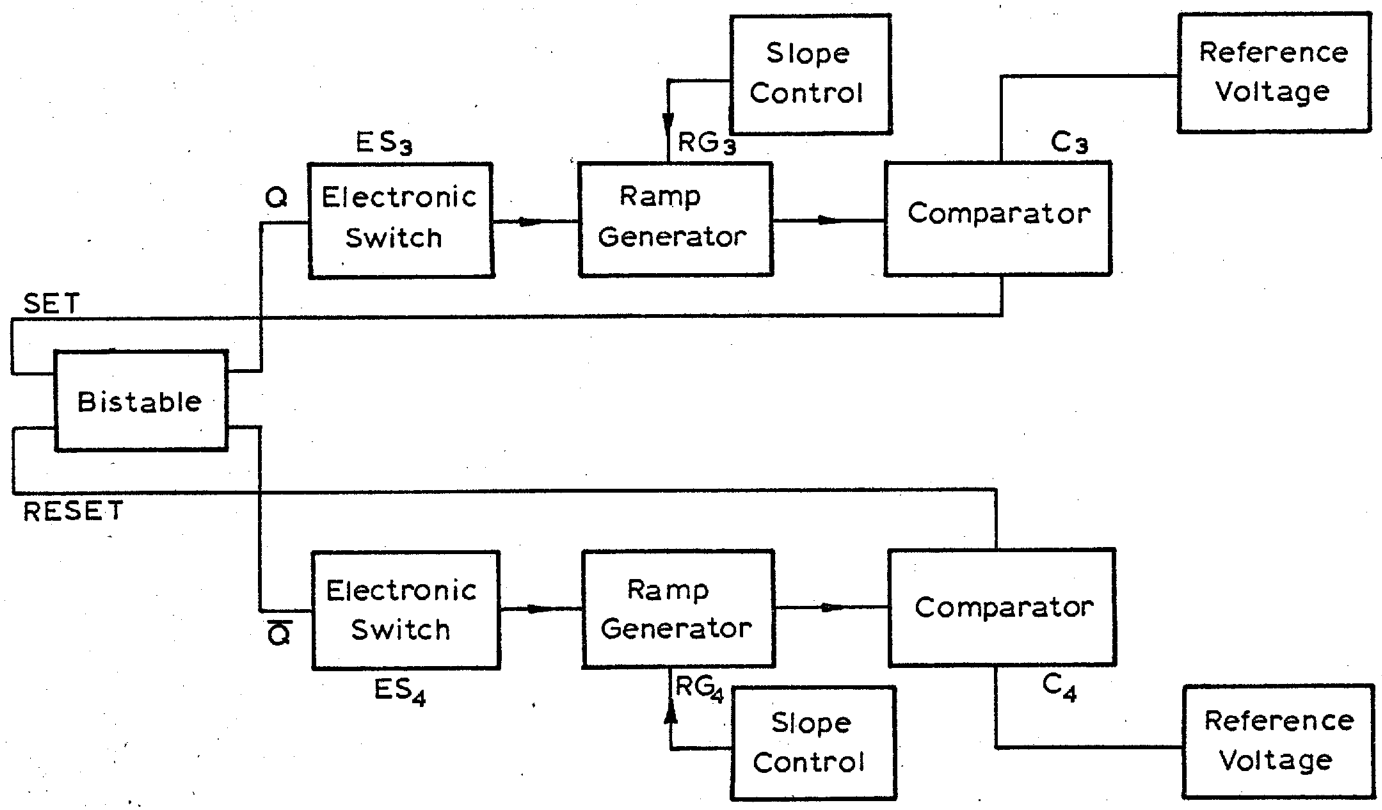


Fig. A.10. Block diagram of the Clock Unit Oscillator pulse; the bistable then goes Q = 1 and RG_4 is now operative until C_4 produces a reset pulse. This system gives a self starting oscillation.

To make this oscillator a monostable (for the one shot mode), RG_4 is made inoperative (the charging capacitor connected to RG_4 is replaced by a small resistor) and the bistable will remain in the set state. A reset pulse will enable the bistable to change state for the length of time specified by RG_3 and C_3.

A.2.6 Calibration of the Delay Section of a Pulse Generator.

The delay function of the pulse generator module is provided with a ten turns potentiometer; a ten turns miniature dial enables a particular delay to be selected with a precision of .5% of the full scale. This may need recalibration from time to time, accordingly we suggest the following procedure.

- Remove pulse generator module 1, 2 and 3
- Insert the module to be recalibrated at the position of module 3. (this procedure gives access to components on the circuit board).
- Set the trigger selector switch (figure A.5) of unit 3, to clock.
- Set the clock period to 50 msec.
- Ensure the unit is not in the "programmable mode". (see section A.2.3 D).
- Set a pulse width of 5 msec, amplitude + 6 volts.
- Set ON (up) the 1 msec delay decade selector, <u>all other selectors down.</u>
- Set the delay vernier to 9.00
- Using a time interval counter, measure the time difference between the clock pulse (prepulse) and the output pulse of unit 3. The counter should read a value near 9000 µsec.

- Adjust the miniature carbon preset (identified on the circuit board by a white paint spot near to it) so as to read 9000 ∓ 30 µsec.
- This procedure assumes that the decalibration was mainly due to small changes in the supply voltage. However if this is due to capacitor ageing, it may be necessary to solder in parallel small capacitors for the decade concerned. For the 1 µsec and 10 µsec decades, the trimming capacitors on the board may be readjusted.

CIRCUIT DIAGRAMS

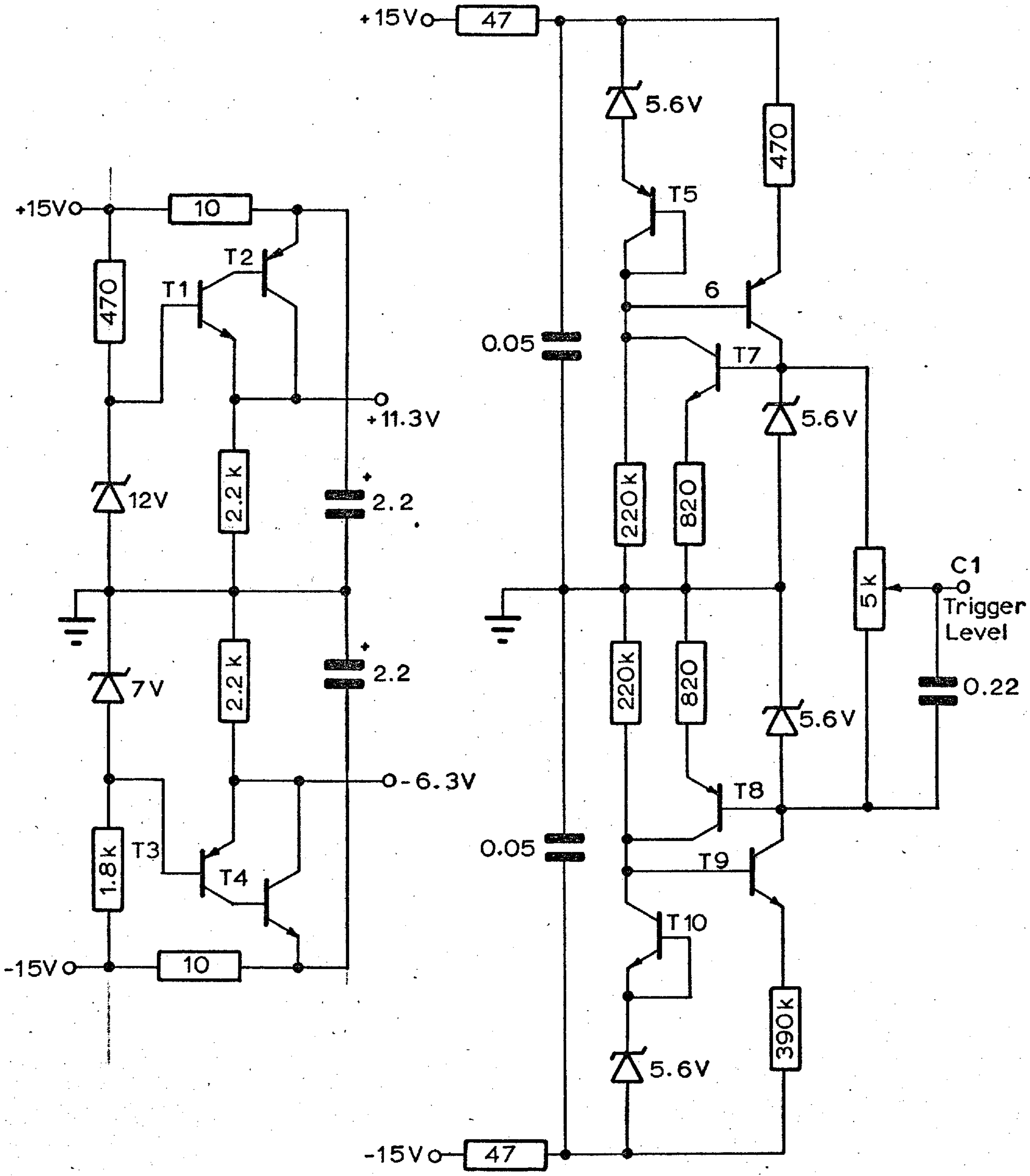


Fig. A.11. Clock Unit Sub-module.
Voltage regulator and reference voltage source

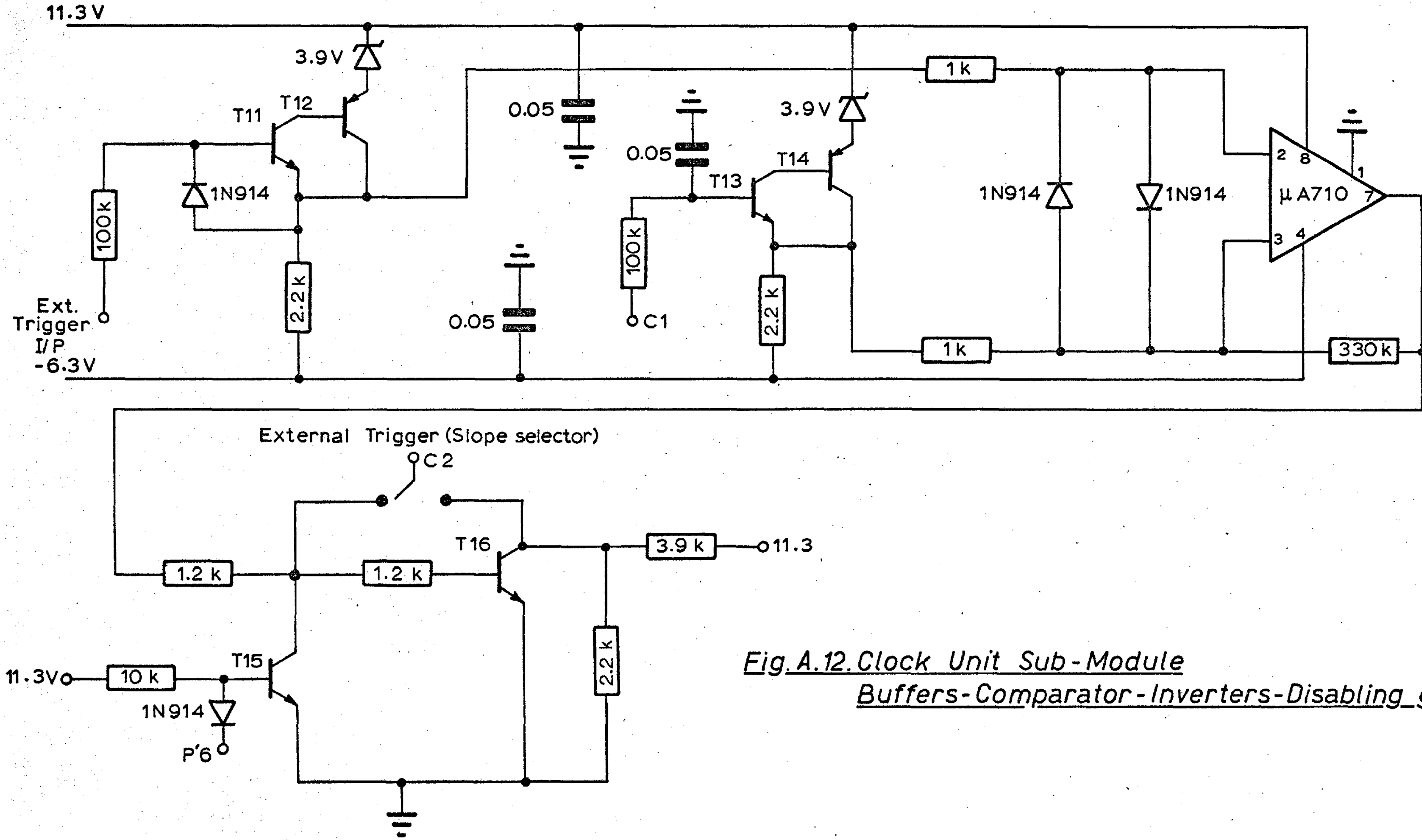


Fig. A.12. Clock Unit Sub-Module
Buffers-Comparator-Inverters-Disabling gate

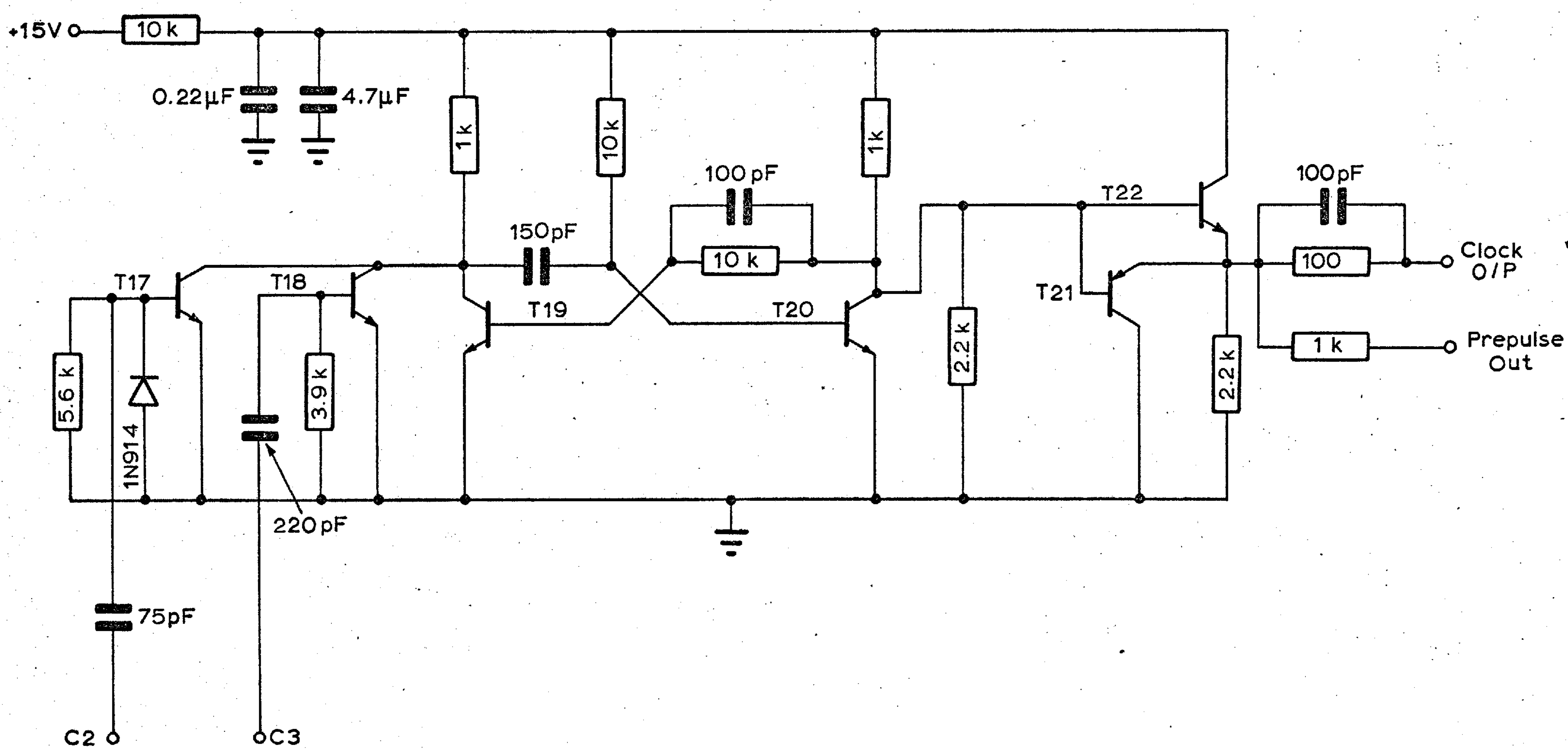


Fig.A.13. Clock Unit Sub Module: Monostable

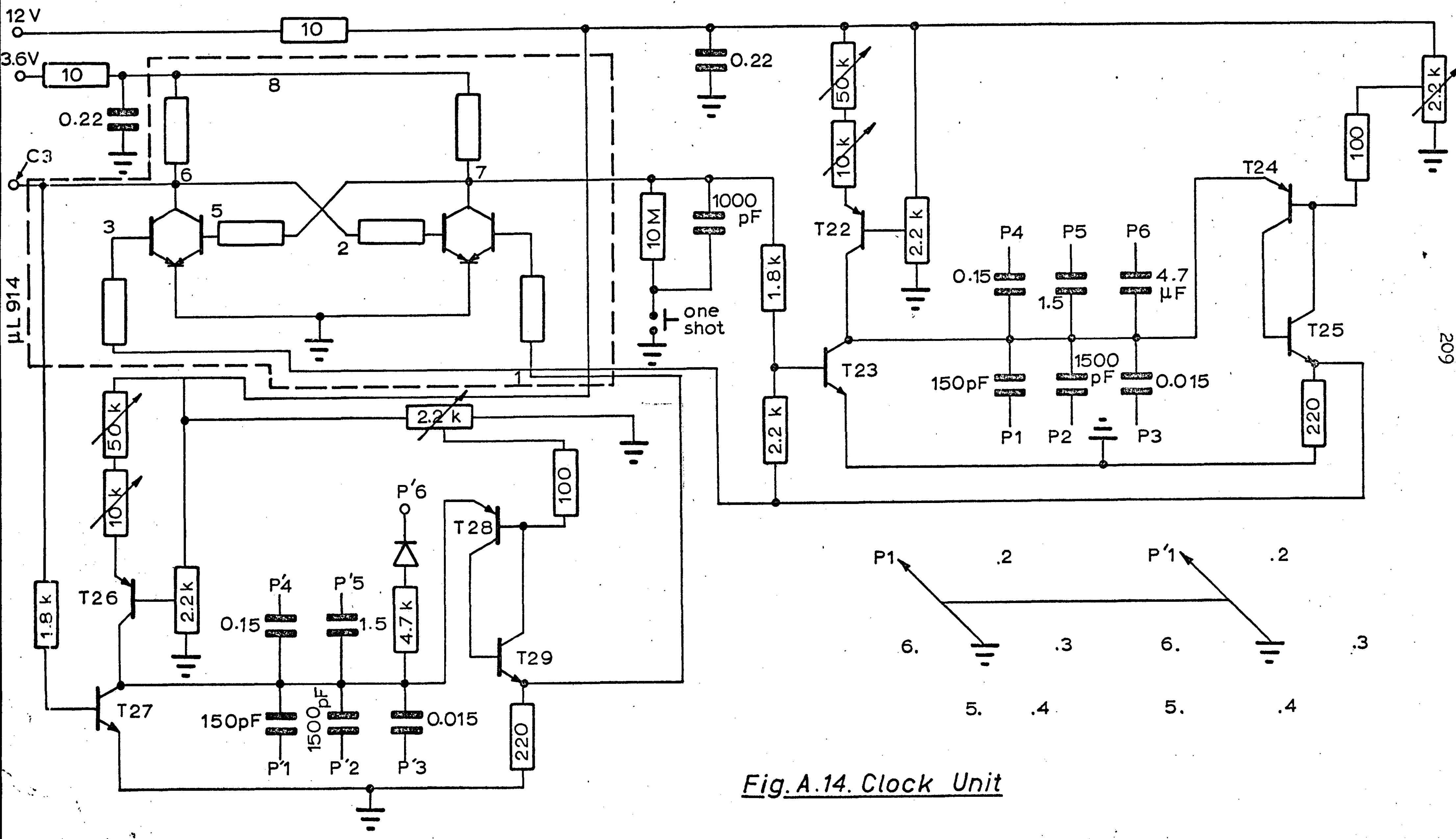


Fig. A.14. Clock Unit

T1,T4	μE 4103
T2,T3	μE 0413
T5,T6	2N 3702
T7	μE 4103
T8	μE 0413
T9,T10	BC 183L
T11,T13	2N 2641
T12,T14	μE 0413
T15	μE 4103
T16	ZTX 311
T17	ZTX 311
T18,T19,T20	TI 647
T22	μE 4103
T21	μE 0413
T22,T26	μE 0413
T23,T27	ZTX 311
T25,T29	ZTX 314
T24,T28	ZTX 510

Table 3 Clock Unit Module. Transistor Identification

1	+ 12 volts
2	+ 3.8 volts
3	NC
4	NC
5	NC
6	NC
7	+ 15 V
8	- 15 V
9	NC
10	NC
11	NC
12	GND
13	
14	
15	
16	
17	
18	
19	
20	Prepulse out
21	Prepulse GND
22	
23	
24	GND

Table 4 Clock Unit: Socket Diagram

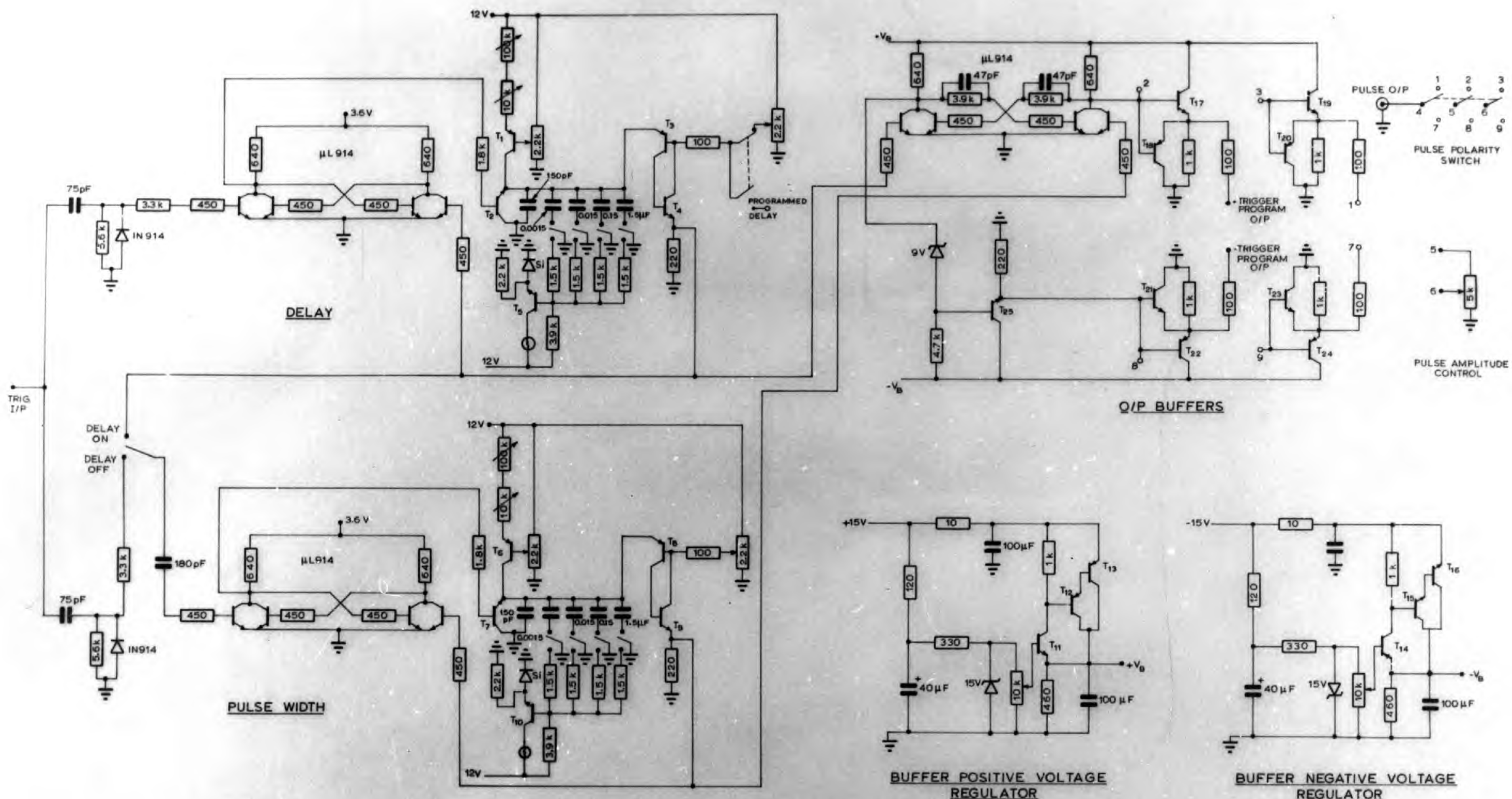


Fig. A.15. Pulse Generator

$T_5, T_{10}, T_{11}, T_{15}, T_{16}, T_{17}, T_{19}, T_{21}, T_{23}$: με 4103

$T_1, T_6, T_{12}, T_{13}, T_{14}, T_{18}, T_{20}, T_{22}, T_{24}, T_{25}$: με 0413

T_2, T_7 : ZTX 311

T_3, T_8 : ZTX 514

T_4, T_9 : ZTX 314

Table 5 Pulse Generator and Buffer Module.

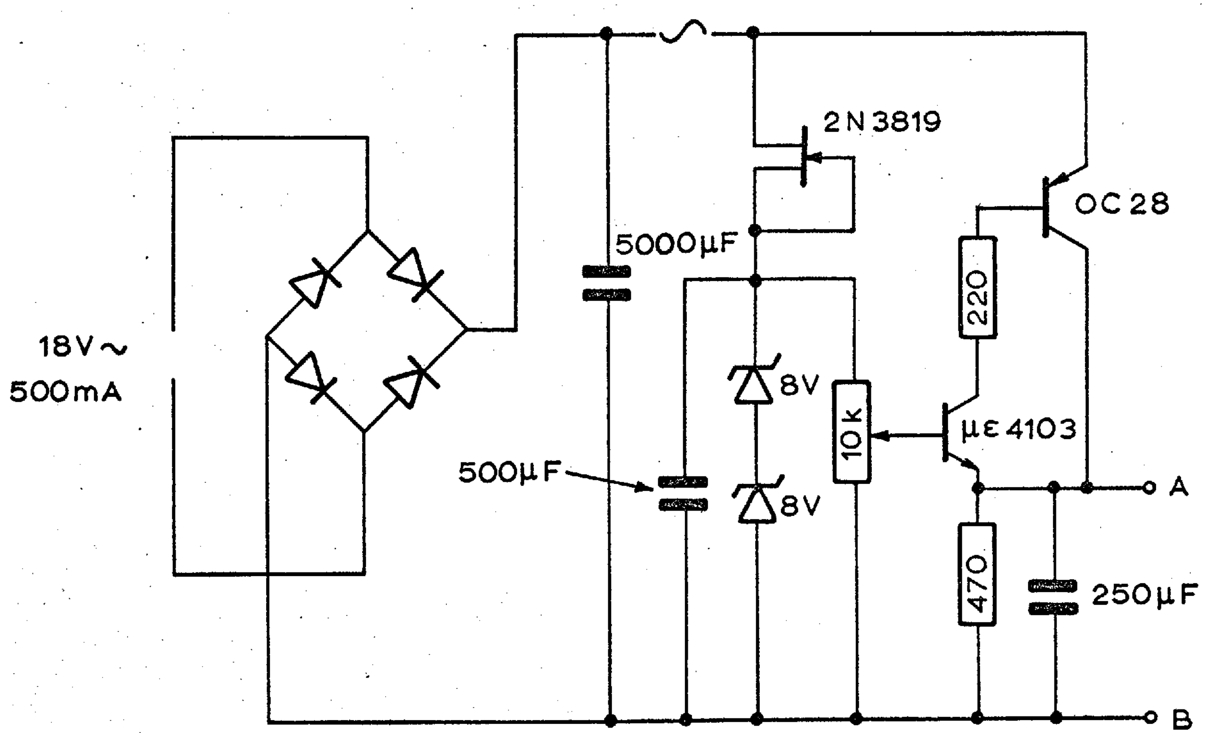
Transistor Identification.

1	+12V	13	Pulse O/P
2	+3.6	14	GND
3	NC	15	Buffer SET
4	Trigger I/P	16	Programmable delay I/P of NC
5	NC	17	NC
6	NC	18	Trigger I/P
7	NC	19	Buffer RESET
8	NC	20	NC
9	NC	21	NC
10	+12V	22	+12V
11	NC	23	NC
12	GND	24	GND

Table 6 Pulse Generator (delay and pulse width module) Socket Diagram.

normal socket (2 units (no.3,no.4)	Inverted socket (3 units(no.1,no.2,no.5))
1	24
2	23
3 Trigger no.3	22
4	21 Trigger no.5
5 Start no.4	20
6	19 Trigger no.1
7 Trigger no.2	18 Trigger no.2
8 Set no.1	17 Set no.1
9 Set no.2	16 Set no.2
10 Clock	15 Clock
11 Set no.3	19 Set no.3
12 Gnd	13 Gnd
13 -15 volts (pulses P.S.)	12 - 15 volts
14	11 Gnd
15 Set no.5	10 Set no.5
16 Set no.4	9
17 Reset no.1	8 Reset no.1
18	7
19 Reset no.5	6 Reset no.5
20 Reset no.4	5
21 Reset no.3	4
22	3
23 Reset no.2	2 Reset no.2
24 + 15 volts	1 + 15 volts

Table 7 Socket Diagram: Buffer unit.



For + 15V Operation:
B ——► Earth
A ——► +15V

For -15V Operation:
A ——► Earth
B ——► -15V

Fig. A 16. +15V and -15V Regulators

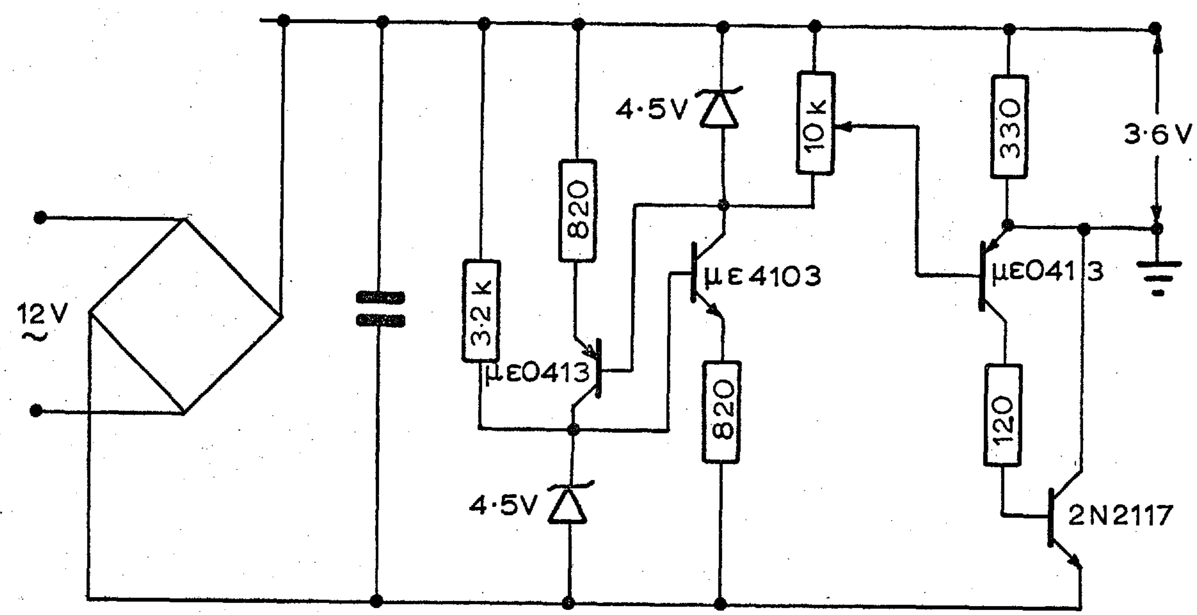


Fig. A 17. 3.6V Regulator

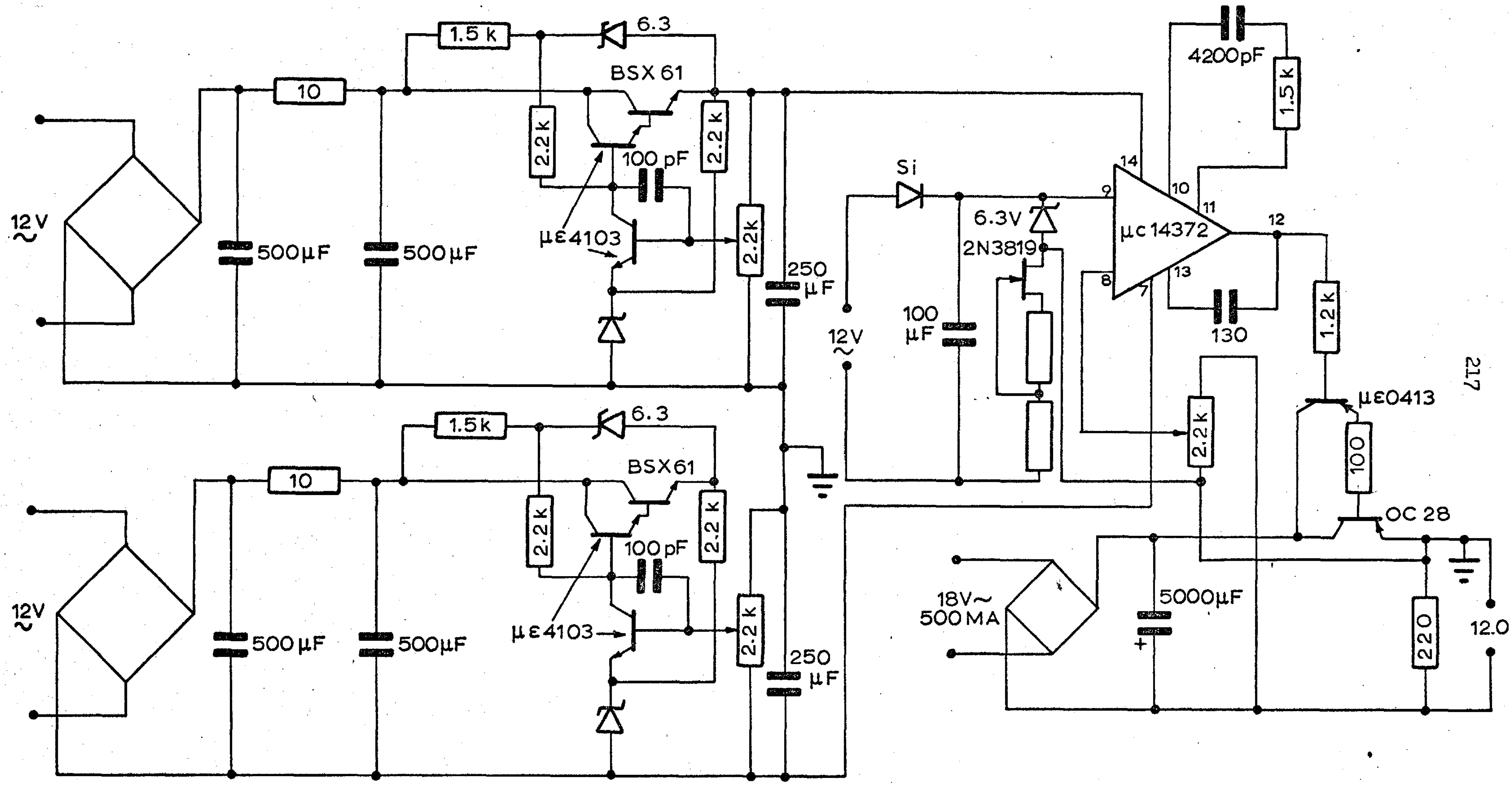


Fig. A. 18. 12 V. precision voltage regulator (temperature stabilized)

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