STUDIES IN ELECTROENCEPHALOGRAPHIC AUDIOMETRY

by

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DECLARATION

DECLARATION

With the exception of the surgical procedures in the animal experiments and the programming of the PDP 12 computer, the work reported in this thesis was instigated and performed by the author.

SUMMARY

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This thesis investigates the application of steady state responses to averaged electroencephalographic audiometry (AEA). Steady state responses may be obtained using either amplitude modulated or frequency modulated stimulation. In both cases the stimulus variables are modulation frequency, modulation depth, carrier frequency and stimulus intensity. Other variables include the number of samples used to compile the average, the stimulus presentation (i.e. monaural or binaural), and the subject state (e.g. awake or under sedation). The effect of these parameters on the responses to both amplitude and frequency modulated stimulation has been investigated for normal hearing adults and children.

For amplitude modulated stimulation the effect of modulation frequency exhibits a large degree of inter-subject variability, while the response behaviour as a function of the other parameters does not. The optimal conditions for audiological assessment have been determined for all parameters with the exception of modulation frequency, which is a function of the individual. For frequency modulated stimulation, the inter-subject variability is small, and optimal conditions have been determined for all parameters.

The steady state response thresholds to both amplitude and frequency modulated stimulation have been determined for adult and child clinical subjects. These thresholds were compared with the behavioural thresholds obtained using conventional audiometry. The responses to amplitude modulated stimulation may be obtained at 20 dB above behavioural threshold, and those to frequency modulated stimulation at 40 dB above behavioural threshold.

Some of the relationships between the two forms of steady state response, the transient response, and the electroencephalogram have been investigated, and the advantages and disadvantages of the steady state responses as an audiological technique have been discussed.

INTRODUCTION

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The detection of hearing loss at an early age is important as it enables prescription of an appropriate hearing aid and the provision of special educational facilities. When these courses of action are properly pursued, the patient has a significantly greater chance of acquiring a normal language function and benefiting from the educational opportunities our society provides.

When an infant shows no behavioural response to a sound stimulus, it is difficult to decide whether the child is really suffering from a defect in the auditory pathway, or whether the absence of a response is due to brain damage, mental retardation or psychosis. Evoked potentials may be used to perform Electric Response Audiometry to assess the hearing of these patients. This thesis describes a refinement of the technique of Averaged E.E.G. Audiometry and assesses its value in the detection of hearing loss.

CHAPTER 1

Electric Potentials in Audiology

1.1 Conventional Audiometry

The standard procedure in the assessment of hearing acuity is the pure tone threshold audiogram, which is obtained by presenting to the subject under test a series of pure tone stimuli of either descending or ascending intensity until the subject indicates the threshold of perception for that frequency (1, 2, 3). This procedure may be automated to scan through both frequency and intensity under the control of the patient to produce a Bekesy audiogram (4).

In all cases the procedure is critically dependent upon the ability and willingness of the subject to indicate the perception or otherwise of a given sound stimulus. This may range from control of the scanning mechanism in a Bekesy assessment, to participation in an identification experiment when dealing with young children (5, 6).

In some cases either the ability or the willingness to perform this task is absent, and assessment may only be achieved using a method which does not rely on the active co-operation of the subject under test. The group unable to co-operate consists mainly of infants and young children, and those unwilling to co-operate consist mainly of older children or adults with non-organic hearing loss.

Reflex reactions to acoustic stimuli may be used for assessment. One common method of infant assessment is the location reflex. The reflex response to high intensity stimuli of the stapedius muscle in the ossicular chain changes the compliance of the tympanic membrane, and this change may be measured with an acoustic impedance bridge (7, 8).

The electrical activity associated with the coding of a sound stimulus in the auditory pathway has received widespread attention and it is the measurement of these potentials to perform electric response audiometry that provides the majority of the techniques of objective audiometry.

1.2 Electric Response Audiometry

An acoustic stimulus is transmitted to the cochlea via the ossicular chain where it is converted into electric impulses in the eighth nerve. From here, via the centres in the brain stem, and up to the auditory cortex, that stimulus is represented as a change in electrical potential in each of the relevant structures. Electric response audiometry seeks to measure and identify these potential changes and in particular to establish the auditory threshold from the threshold of the electric response.

At the peripheral section of the pathway, the eighth nerve action potentials are investigated to assess cochlear function; this technique is known as electrocochleagraphy (9, 10). At the cortical level of the pathway, the changes in the electroencephalogram (EEG) produced by a sound stimulus may be measured, leading to the technique of averaged electroencephalographic audiometry (AEA), which forms the basis for this thesis. Of course the activity from intermediate levels of the pathway may be measured; a description of the available electric potentials is given by Davis (11).

1.3 Averaged EEG Audiometry (AEA)

The technique of averaged EEG audiometry uses as an indicator of auditory function, the mean change in an EEG channel in response to a series of sound stimuli. It is not possible to use the change in the EEG produced by a single sound stimulus as this is smaller than the magnitude of the ongoing EEG. Typically the amplitude of the EEG change may be between zero to 10 uV depending on the intensity of the stimulus.

To extract the required signal (i.e. the response) from the ongoing EEG (which is regarded as unwanted noise) the technique of signal averaging is used, enhancing those portions of the signal which are time-locked to the stimulus. The principle of signal averaging has been established since the early nineteenth century, but it was the demands of radar during the last war which forced the necessary technological development. A statistical treatment of signal averaging is given in Appendix 1.

A series of sound stimuli (typically 50 tone bursts of about 300 ms duration) are presented to the subject at intervals of about one every two seconds. The corresponding fifty sections of EEG activity (each segment is usually one second in length) are summed and normalised in the averager. This averaging device then contains the change in the EEG due to the sound stimulus. For the reasons given in Appendix 1, the average always contains some residual EEG activity as well as the response component.

Figure 1.1 shows an idealised response waveform, with no residual noise component, and a real response. The four principal components are conventionally labelled P1, N1, P2 and N2 (12). There do exist earlier components in the response which occur prior to P1 (13) but it is the later components which received the primary application in threshold determination.

To establish a threshold using the responses, the stimulus intensity is successively decreased until the response waveform is no longer present. As the intensity is decreased, the amplitude of the response decreases and the latency increases (14, 15, 16). Figure 1.2 illustrates the change in the response as the intensity is decreased from well above threshold to a level where the response can no longer be easily recognised.

Exhaustive tests have been performed using AEA. Its place in audiological assessment is established (17, 18, 19) though there are problems in its application. Some of these will be discussed in the

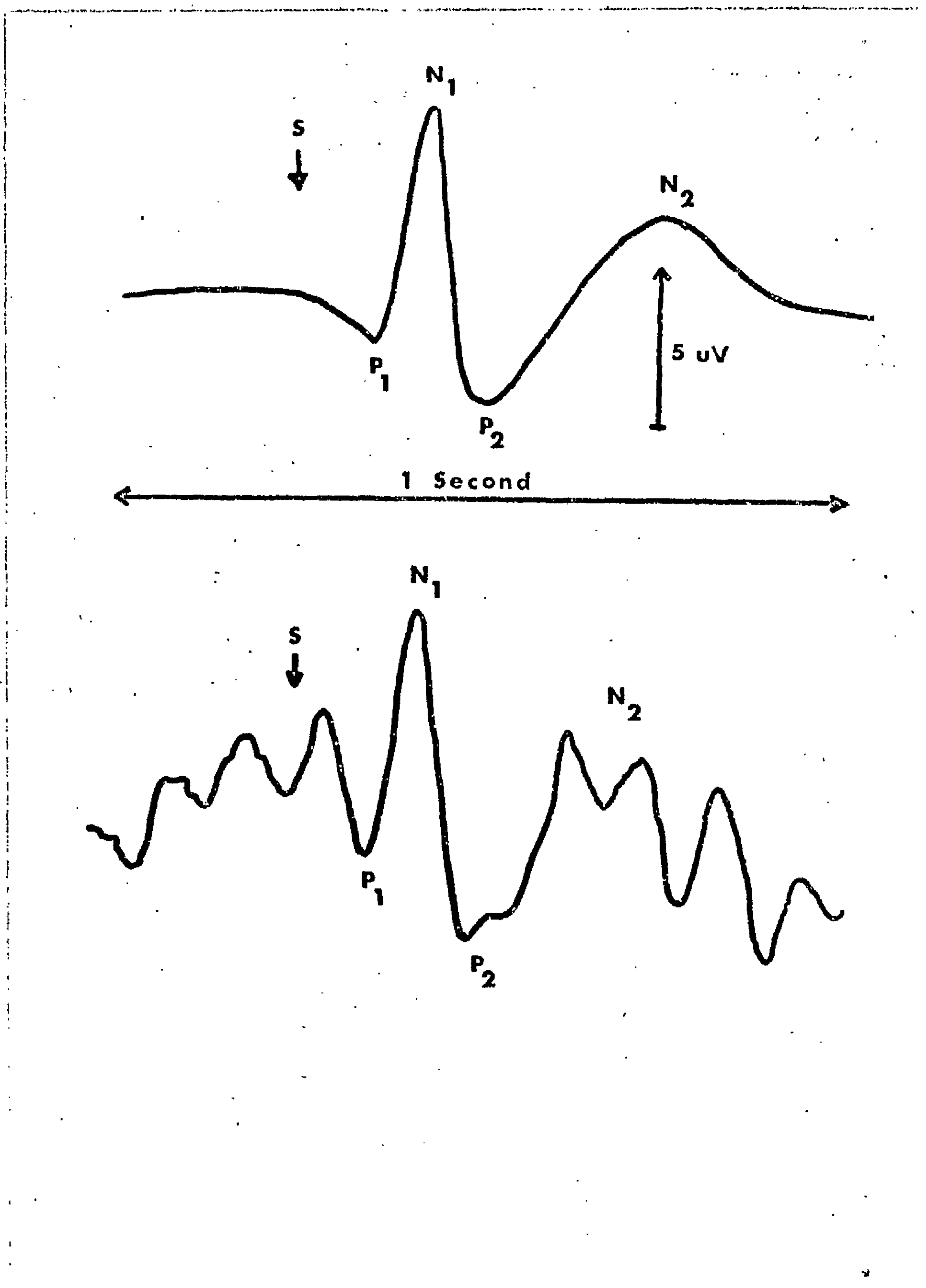


Figure 1.1 Idealised and Real Response Waveforms for Transient Stimulation.

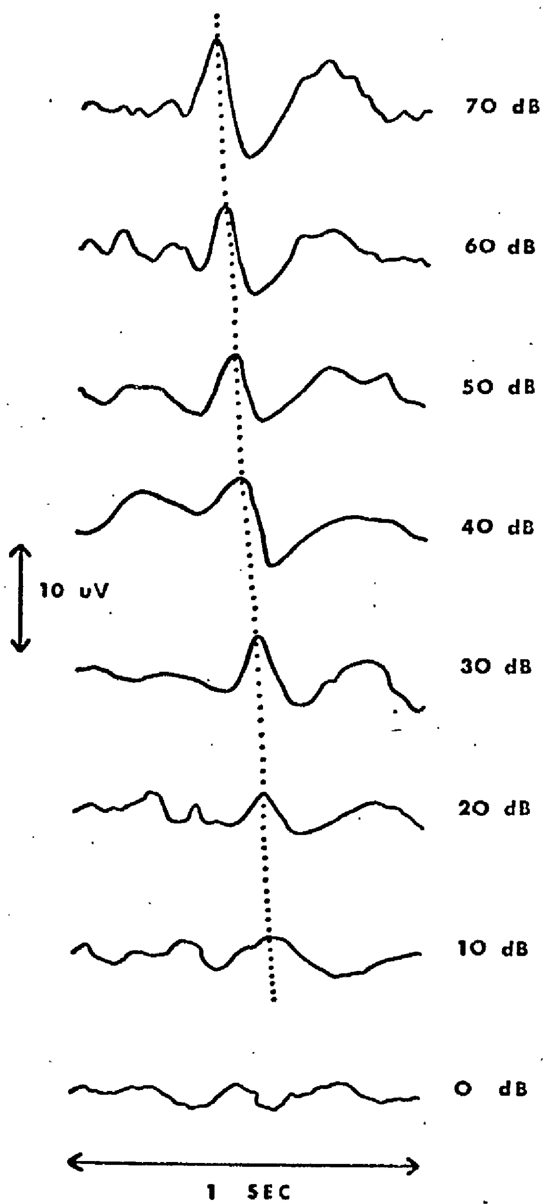


Figure 1.2 Transient Response Waveforms at Different Stimulus Levels.

next section. One particular success of AEA has been the assessment of non-organic hearing loss in older children and adults (20).

There is no a priori reason why the threshold of detectability of the averaged EEG response should be the same as the behavioural threshold to the stimulus. In fact it is found (21, 22) that the electrophysiological threshold is about 10 dB less sensitive than the behavioural threshold. This is thought to occur due to the difficulty in recognising the presence of the complex response waveform in residual EEG activity at low stimulus intensities where the residual activity may be as large as, or larger than, the response.

1.4 Problems with Averaged EEG Audiometry

The problem of recognition of the response pattern in residual EEG has been mentioned above. Other problems arise from the nature of the subjects to whom AEA is most applicable.

A great many referrals consist of young children under five years of age, where the form of the response may differ markedly from the adult waveform (23, 24), usually but not always having the later slower components prevailing. Fig. 1.3 shows responses from eight children between the ages of 2½ and 4 years old. The waveform for each child was found to be stable for each individual over the course of at least three days. The inter-subject variability is clearly demonstrated and many responses differ markedly from the adult response (shown in Figure 1.1). This variability enhances the problems of response recognition. Also the fact that the ongoing EEG activity in younger subjects is significantly greater than for adults, leads to a larger component of residual EEG in the final average.

Another problem in the assessment of young children is their lack of co-operation, in that excessive movement may make impossible recognition of any response present, due to large muscle potentials or eye movements for example. This is illustrated in Fig. 1.4, where A is the normal

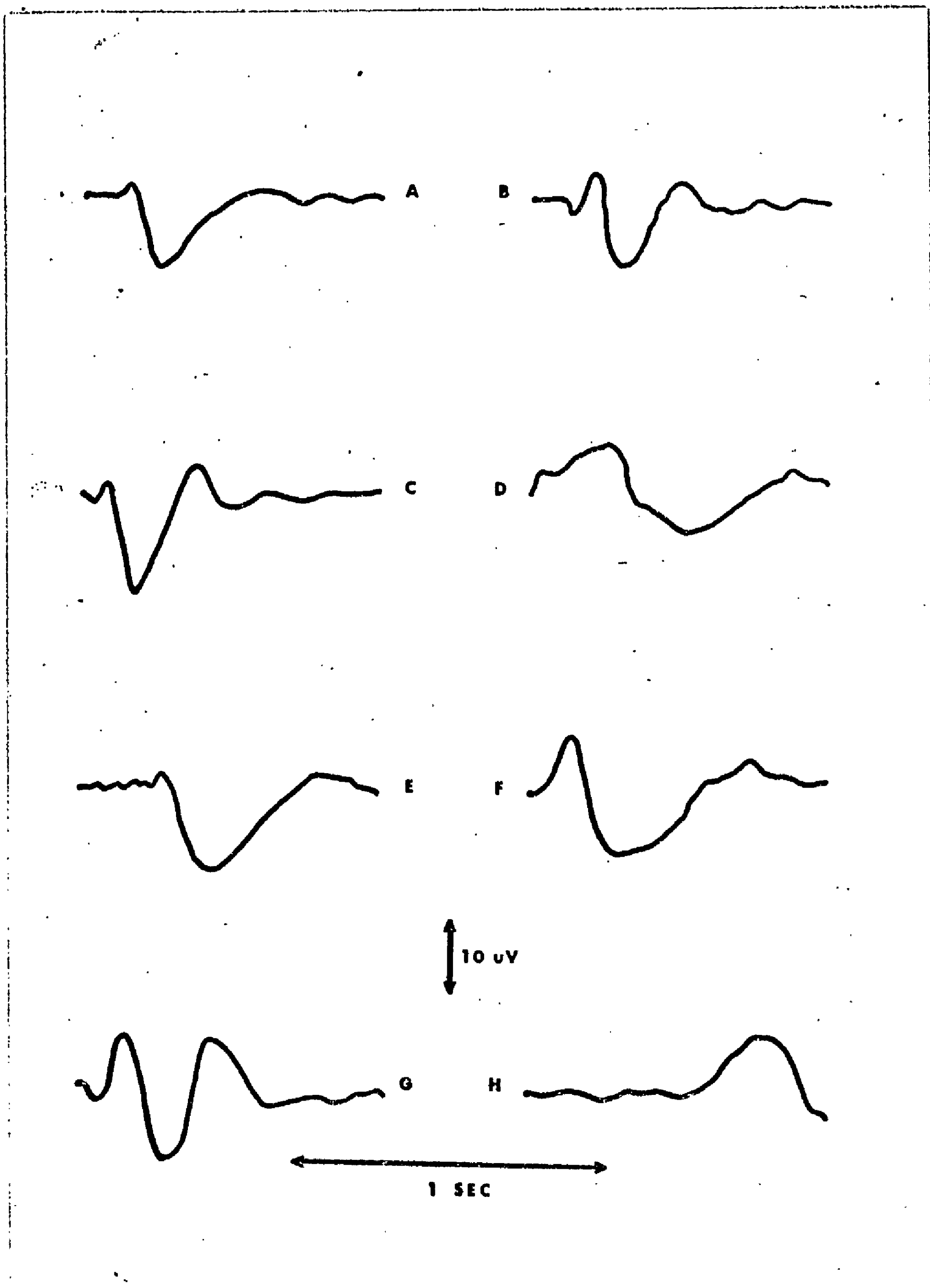


Figure 1.3 Transient Response Waveforms for Eight Children.

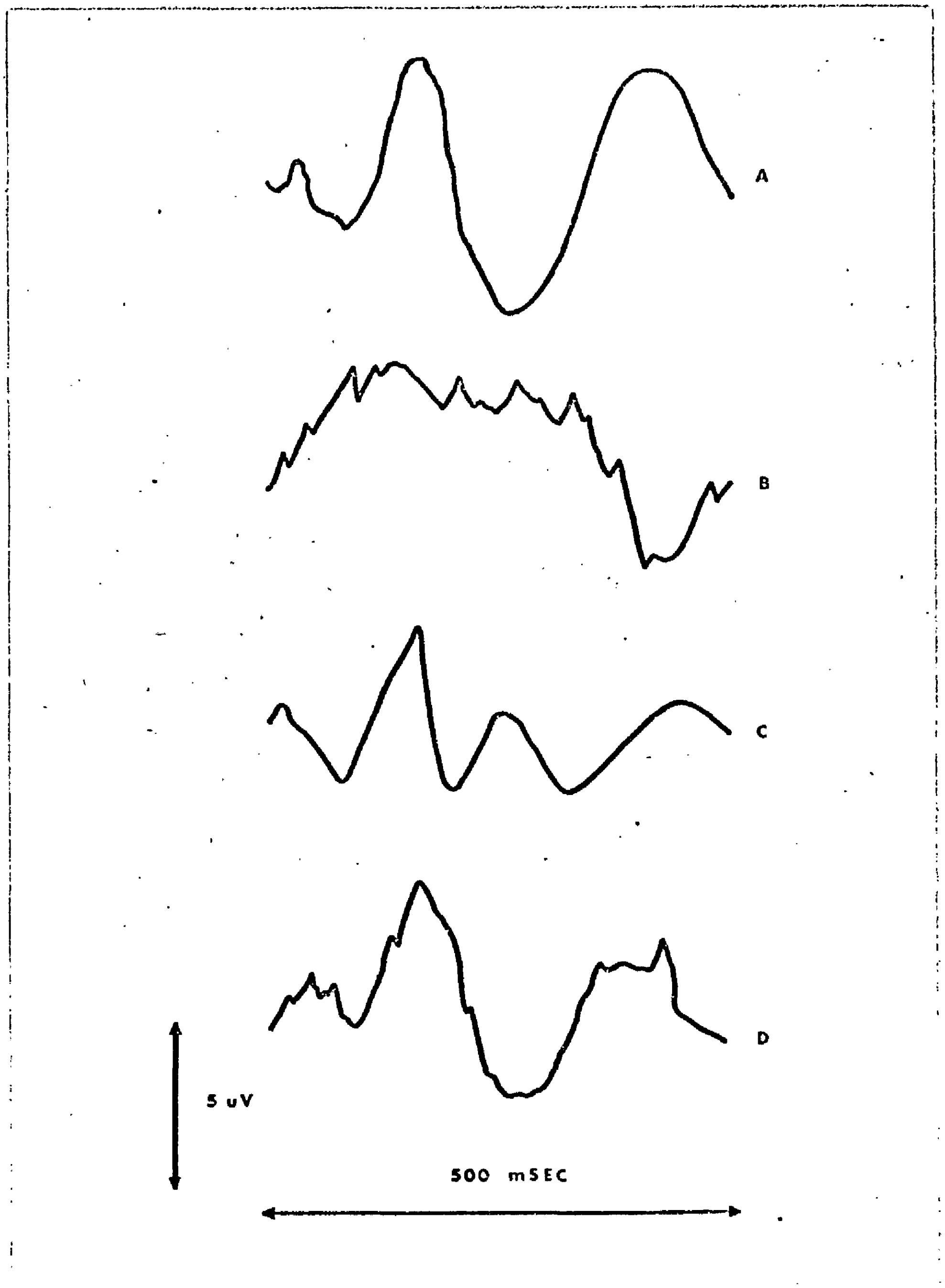


Figure 1.4 Effect of movement on the Transient Response.

A - Sitting quietly.

B - Crying.

C - Blinking.

D - Talking.

response from an adult in a relaxed sitting position. In B the same adult mimics a hyper-active child by crying and excessive head movements. This may be seen to overwrite any response. In C the adult blinks throughout the test session and in D talks continually. Also the degree of attention paid by the subject to the stimulus may affect the response (25, 26).

In an attempt to minimise any movement artefact, a sedative may be administered. However, this raises the problem that the action of the sedative may itself affect the response (27, 28, 29, 30, 31). There is no general agreement on the optimal sedative or on detailed effects, as the reaction seems to be very much related to the individual.

The end result of the above difficulties is that AEA carries significantly less reliability when applied to children (21, 32) than to adults.

1.5 Techniques to improve averaged EEG audiometry

The effectiveness of averaged EEG audiometry may be improved by (a) rejection of large voltage and other artefacts in the ongoing EEG, (b) better recognition of the response by more sophisticated analysis, and (c) improvement of the response itself by alteration of the sound stimulus.

Movement artefacts and eye blinks are characterised by large voltage swings in the EEG. It is possible to pre-set limits on the input to the averager so that only EEG signals which are within these limits are used to compile the average, and all large excursions thus omitted (33).

The difficulty in recognising the response in residual EEG can lead to a large degree of inter and intra-observer variation (34), even when the tests are performed on a group of co-operative adults. The variation may be significantly larger when dealing with children. To counter this, several methods of machine scoring and template analysis have been developed (35, 36) to remove the need for a subjective observer decision.

These methods necessarily involve complex computer techniques, as the response they try to recognise is itself complex.

A tone burst may not be the most effective means of eliciting a response. Averaged EEG responses to frequency change (rather than loudness change) have been investigated (37, 38, 39) with encouraging results and Spoor et al (40) have used bursts of intensity modulated and frequency modulated tones.

In all these techniques the fundamental problem remains, that the response is not amenable to analytical description, and because of its complex nature, is difficult to identify.

1.6 Steady State Potentials

Steady state potentials are elicited by continuously presenting to the subject a sinusoidally modulated stimulus, whence the response takes the form of a periodic signal whose fundamental (first harmonic) is at the frequency of modulation. Steady state potentials to visual stimuli have been extensively investigated, and a comprehensive review is given by Reagan (41).

Transient evoked potentials (i.e. potentials evoked by a series of tone bursts or clicks for auditory stimulation) are elicited by stimuli that are sufficiently widely spaced for the system to be regarded as returning to rest between each stimulus. In fact transient evoked potentials may be regarded as elicited by a continuously presented carrier (in this case a pure tone) which is square wave modulated at a slow rate. It is usual to describe a transient evoked potential in terms of the amplitude and latency of the different recognisable components of the waveform (e.g. P1, N1, P2 and N2 of Figure 1.1).

Transient evoked potentials to repeated stimuli overlap to an increasing degree as the stimulus repetition rate (that is, the modulation frequency) is increased. At sufficiently high modulation frequencies no individual response cycle may be identified with any individual stimulus cycle. This situation is referred to as "steady-state" and it is no longer appropriate to describe the response waveform in terms of the latency of its components (i.e. describing the response in the time domain). It is more suitable to describe the response in terms of harmonics of the modulation frequency (i.e. describing the response in the frequency domain).

It is convenient to use a harmonically simple (e.g. sinusoidal) stimulus waveform, as any higher harmonics (i.e. any non-linearity) are then due to the pathway under investigation. The analysis of a repetitive (i.e. periodic) waveform in terms of its harmonic components is known as Fourier analysis, and a description of this technique is given in Appendix 2. Fourier analysis provides a precise description of the steady state waveform in terms of both amplitude and phase, and the waveform may be described as a linear sum of sinusoidal terms.

The frequency F Hz (the modulation frequency) at which the waveform repeats itself is the fundamental or first harmonic and the higher harmonics are multiples of F. Results using visual stimulation (42) have shown that only a small number of harmonics (as low as 2 in some cases) may be required to describe the evoked potential waveform and, if similar results occur using auditory stimulation, the waveform may be simply described in analytical terms.

Acoustically evoked steady state potentials have been reported in dogs (43) and in two human subjects (44). In both cases the results are very similar to those obtained using visual stimulation.

1.7 Plan of Investigation

The aim of the investigation is to assess the applicability of acoustically evoked steady state potentials to audiometric assessment. Some of the problems encountered using transient stimulation have been described, and the potential advantage of the steady state situation is that the response waveform takes the form which may be more readily described in analytical form. This means that the observer is able to more easily construct definitive criteria when faced with the problem of recognition of a response waveform in residual noise.

When using transient stimulation, both an intensity change and a frequency change evoke a response (37), and it is therefore likely that both intensity (amplitude) modulation and frequency modulation can evoke a steady state response. Optimal stimulus parameters such as modulation frequency and modulation depth require to be determined, and the ability of the responses to predict behavioural threshold investigated. Younger children will still require sedation; therefore the effect of sleep inducing drugs should be known. The following chapters attempt to provide answers to these unknowns.

CHAPTER 2

Experimental Techniques

2.1 Introduction

Two forms of stimulus presentation are used; a sinusoidally amplitude modulated pure tone and a sinusoidally frequency modulated pure tone. A trigger signal at the frequency of modulation is provided to construct a single cycle average for on-line analysis, and the EEG signals and the trigger are recorded on a tape recorder for later analysis.

2.2 Stimulus Generation

(a) Amplitude modulated tone:- A block diagram of the system used for the amplitude-modulation (A.M.) experiments is shown in Fig. 2.1. The modulator is based on a Silicon General SN3402N integrated circuit, arranged so that stable operation is achieved in the range 250 Hz to 8000 Hz for the carrier frequency and 4 Hz to 20 Hz for the modulation frequency. The modulation depth is variable from 0% to 100% in steps of 10% by switching a pre-set potentiometer network. The carrier signal is derived from a Bruel and Kjaer beat frequency oscillator, and the modulation sinusoid and trigger square wave from a Hewlett Packard 3300A function generator. A Brookdeal 9421 phase shift module is built into the modulator input to ensure a constant phase relationship between the modulated output and the trigger signal. In fact the phase difference between the two signals was set to zero.

The modulated signal is monitored on an oscilloscope and delivered to the subject via the external input of an Amplaid audiometer to calibrate the appropriate stimulus intensity in terms of dB HTL (Hearing Threshold Level).

(b) Frequency Modulated tone:- The system for the experiments using frequency modulation is shown in Fig. 2.2. The external frequency

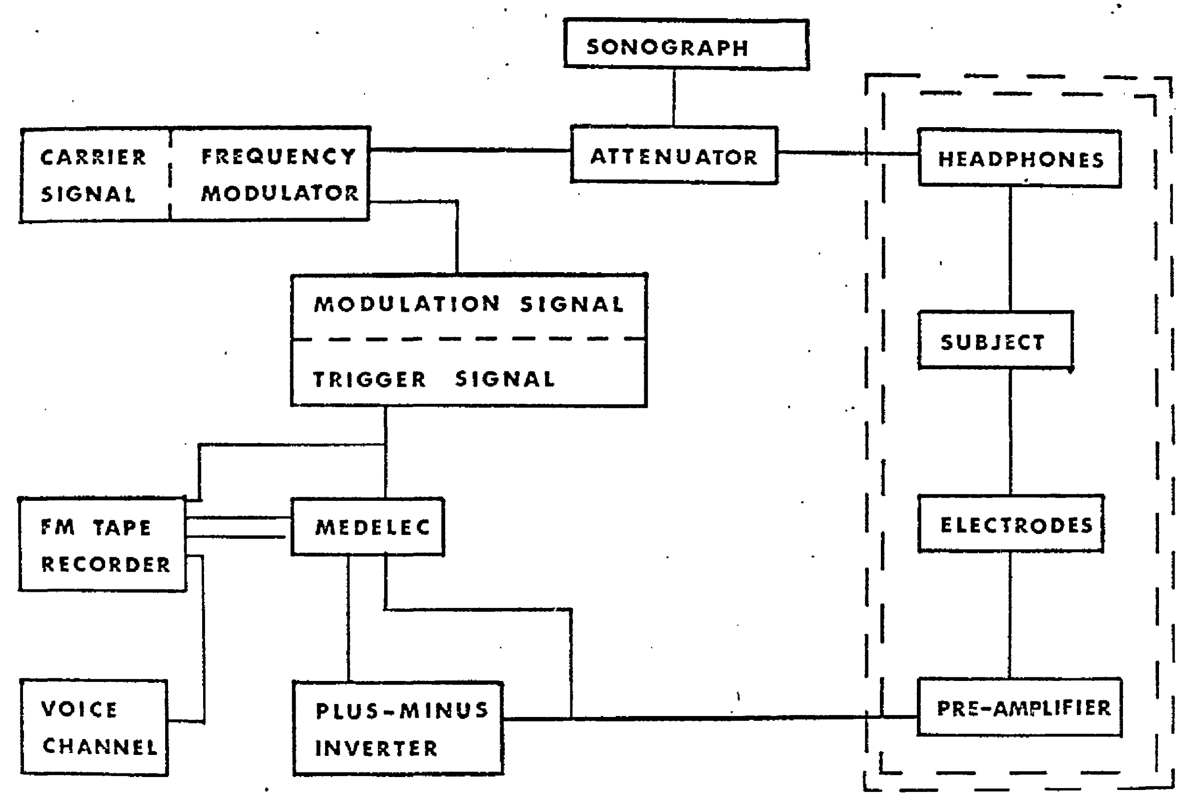


Figure 2.1 Experimental System for Amplitude Modulated Stimulation.

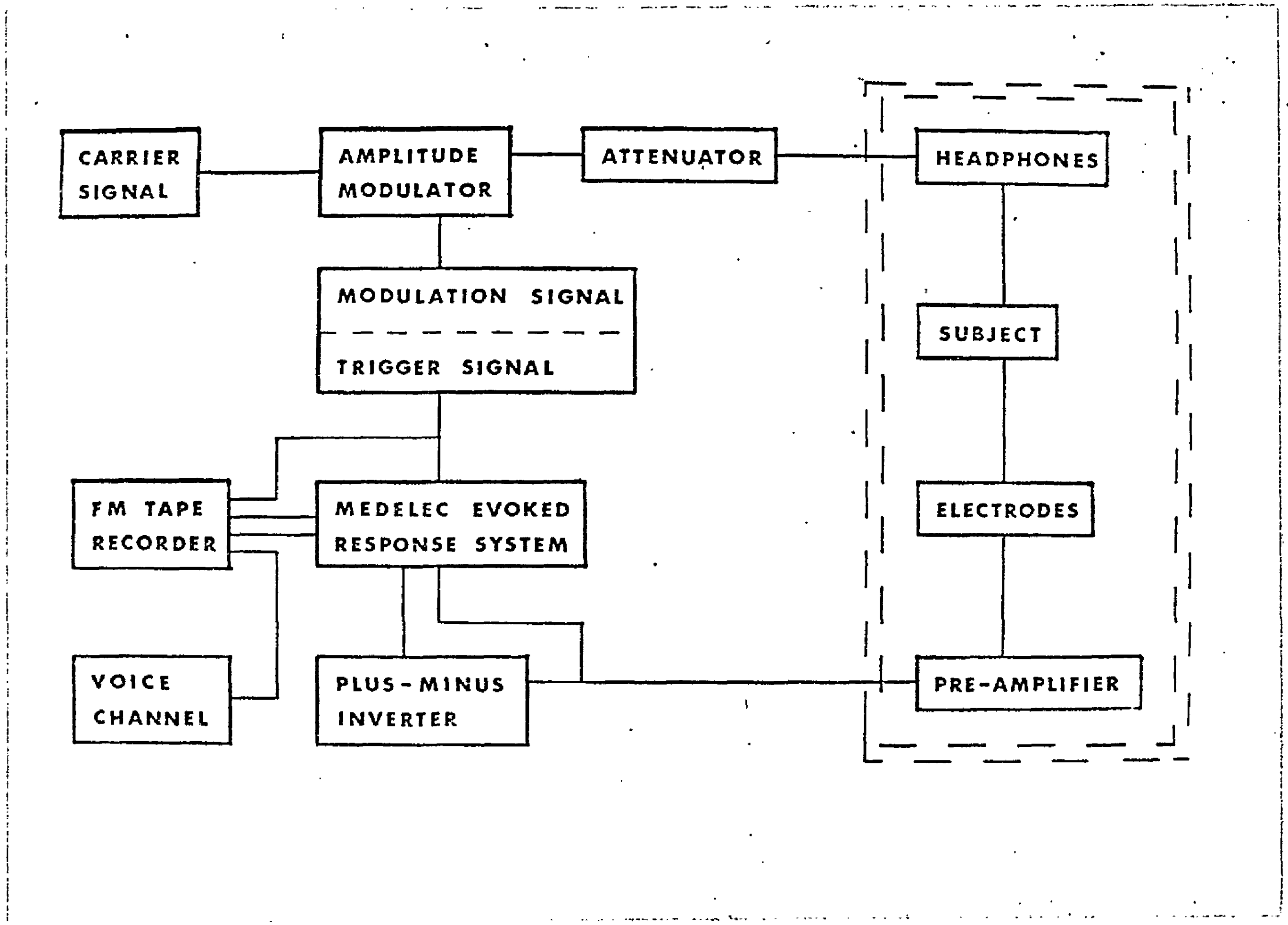


Figure 2.2 Experimental System for Frequency Modulated Stimulation.

modulation facility on the Bruel and Kjoer oscillator is used to achieve the required modulation. Again the modulation signal and trigger are provided from the Hewlett Packard function generator, and a stable phase relationship between the modulation and the trigger is established. A Kay Sound Spectrograph (Sonograph) is used to monitor the modulated signal and measure the modulation depth. An auxiliary loudspeaker output from the Amplaid audiometer is fed back to the compressor input of the beat frequency oscillator via a condensor microphone to ensure that the sound pressure level delivered to the subject remains constant. This is necessary as some of the components in the system have a non-linear frequency response (for example, the external amplifier on the audiometer), and a constant sound pressure level is required to differentiate between evoked potentials to intensity and frequency change.

2.3 Acquisition of the EEG

The subject is isolated as far as possible from the experiment, and is asked to sit and read quietly in a sound reduced room, from material of his own choice. Silver-silver chloride cup electrodes are used to derive an EEG signal from the vertex with reference to mid-line on the forehead. A ground electrode is placed on either mastoid. A Medelec pre-amplifier is placed close to the subject and the EEG is filtered to pass frequencies in the range 3.2 Hz to 64 Hz. The EEG signal is recorded on a Racal T3000 FM tape recorder run at a speed of $1\frac{7}{8}$ i.p.s. The trigger signal is also recorded and a voice channel is added to aid identification of the experiment.

For some of the experiments, multi-channel recordings were required. In this case a Type T Offner electroencephalograph was used to derive the EEG signals which were then recorded on an Ampex SP300 tape recorder.

2.4 On-line Analysis

The on-line analysis is performed as an indication of the suitability of recordings for further study, and in the case of the preliminary experiments, as a check that responses are actually being elicited. The Medelec evoked response system is used to monitor the averages obtained. The trigger signal is used to set the averaging time (commonly referred to as the "window") equal to one period of the modulation signal, and hence trigger the averager once for every cycle of modulation. The averages generated are referred to as "single cycle averages". As well as the normal average, a second channel in the Medelec system is used to generate a "plus-minus" average (45). A more detailed treatment of this procedure and the electronic circuit to perform the function are given in Appendix 3. Briefly, it is a measure of the residual noise after averaging and is constructed by alternately adding and subtracting the sections of EEG in the averager, rather than simply adding in the sections, as in the normal average.

Thus two averages are available, one consisting of response plus residual noise (the normal average) and one consisting of residual noise (the plus-minus) (±) average. Examples of single cycle averages for both the normal and plus-minus averages are shown in Fig. 2.3. It is possible to compare the two types of average for significant differences to see if any response is present.

All preliminary experiments were performed using averages constructed from 1024 cycles of modulation, which gives a theoretical improvement in signal to noise ratio of $\sqrt{1024}$. An automatic rejection device is built into the averager so that sections of EEG containing large voltage excursions are not included in the final input to the averager.

2.5 Off-line Analysis

Further analysis is performed on a Digital Equipment PDP12 computer. Single cycle averages are obtained in the same manner as the off-line analysis, with the square wave from the tape recorder acting as a clock signal to both set the averaging window and initiate the input to the

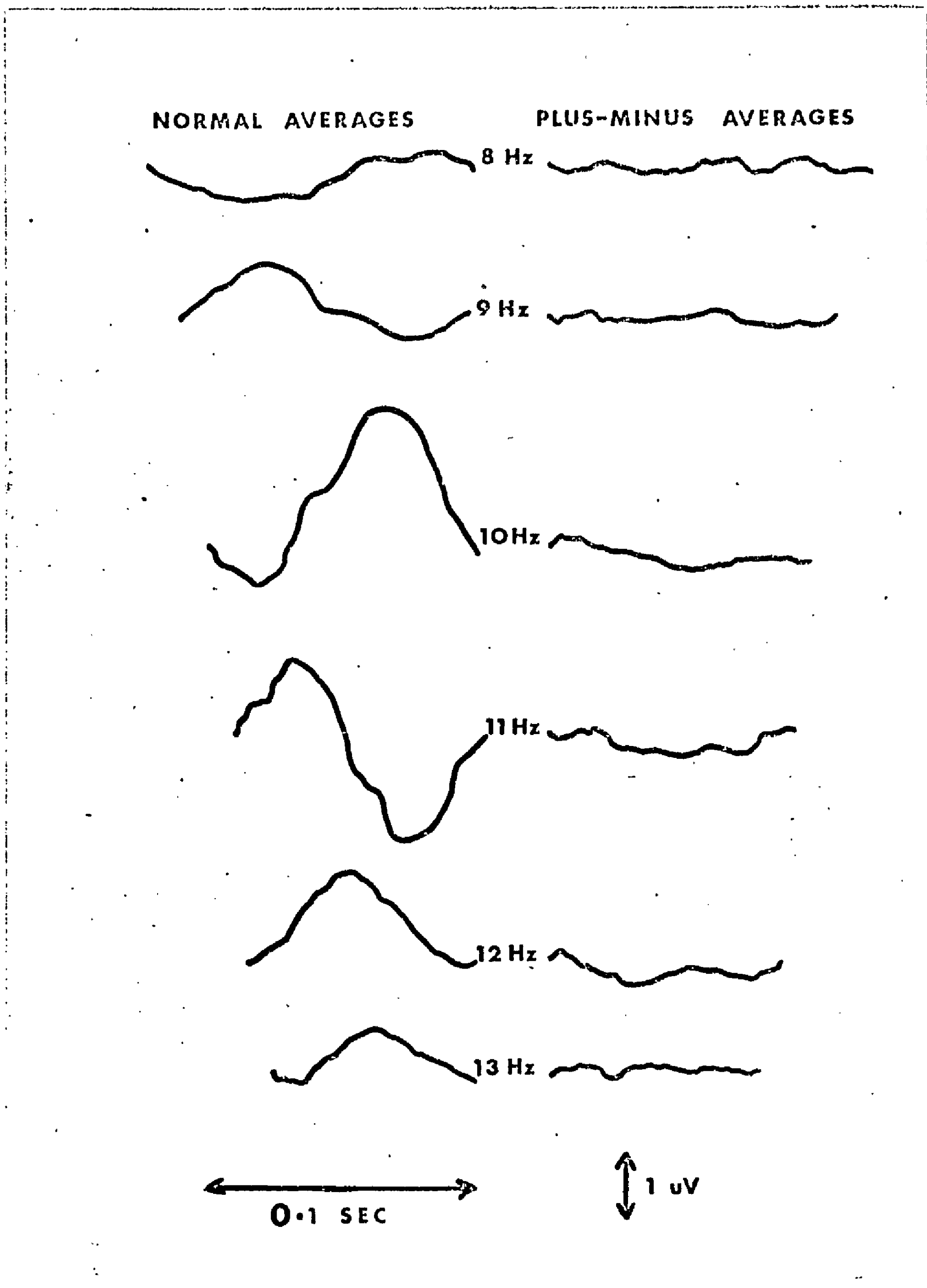


Figure 2.3 Examples of Single Cycle Averages.

averager for each cycle of modulation.

To obtain a periodic signal suitable for frequency analysis, the single cycle averages are repeatedly played into the memory core until a signal equivalent to four seconds duration is obtained. These averages are referred to as "periodic averages". This procedure is very similar to that employed by Rodenberg et al (44). For example, at a modulation frequency of 10 Hz, forty single cycle averages are repeated to form a four second long periodic signal. Examples of sections of these periodic averages are shown in Fig. 2.4, for both the normal average and the plus minus average.

The periodic averages are analysed into their harmonic components using a Digital Equipment fast Fourier transform and display program (FFTDEAE) which describes the waveform in terms of the amplitude and phase of a series of sinusoids, (Appendix 11). Examples of the amplitude components are shown in Fig. 2.5 for the two types of average for subject A. For the normal average the first harmonic is clearly the principal component. The amplitude of the first harmonic is calibrated in μV using a test sinusoid.

An approximation to the response spectrum alone may be obtained by subtracting the noise spectrum (the plus-minus average spectrum) from the response plus noise spectrum (the normal average spectrum). Fig. 2.6 shows the variation of the amplitude of the first harmonic with modulation frequency for subject A for (a) the uncorrected spectra (i.e. the spectra of the normal average) and (b) the corrected spectra (i.e. the subtracted spectra). It can be seen that the effect of applying this simple approximation is to remove some of the irregularities in the frequency response curve. The variation of the first harmonic with modulation frequency will be discussed in detail in Chapter 3.

2.6 Artefact Considerations

It is important to ensure that the potentials evoked are not the

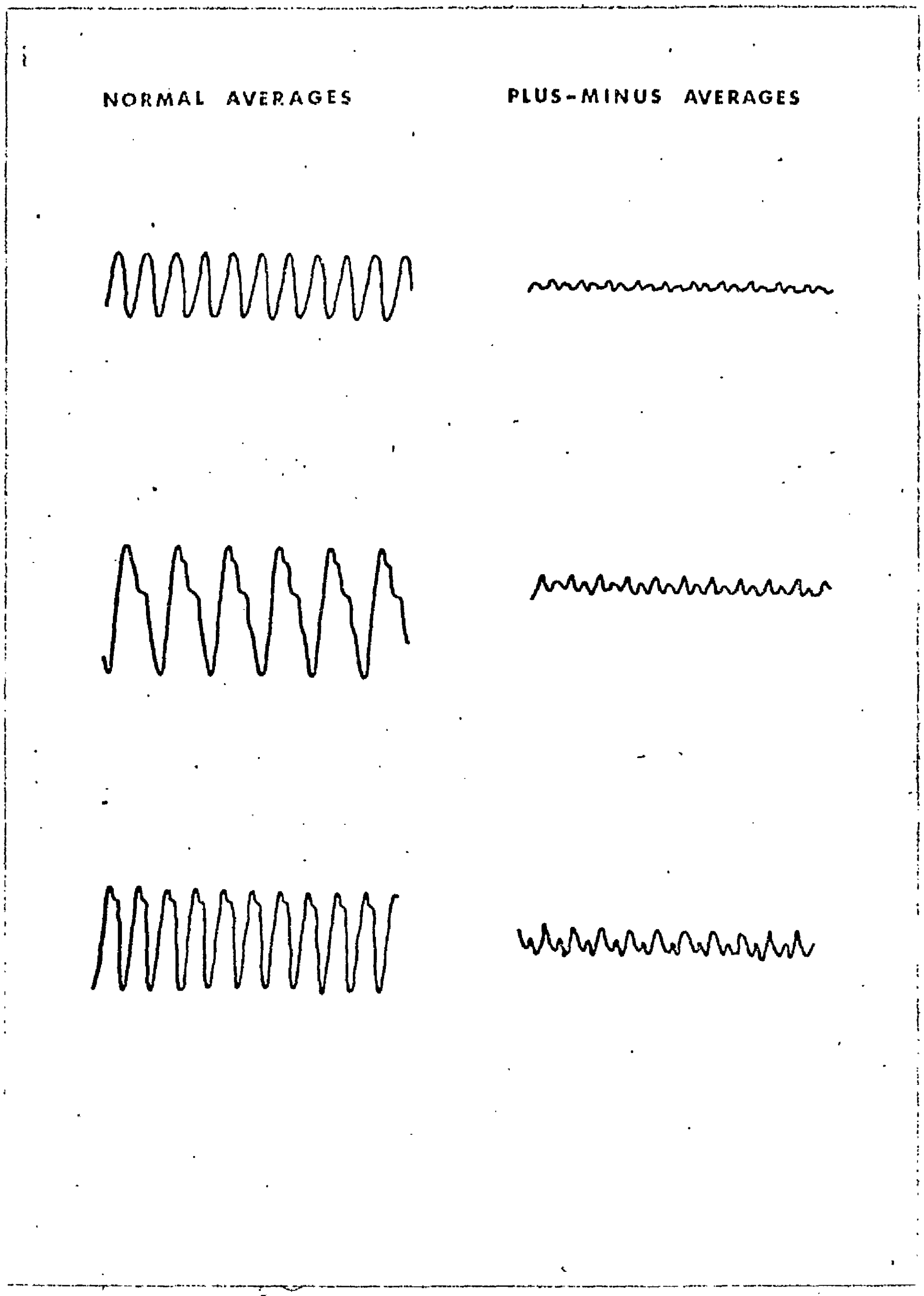


Figure 2.4 Examples of Periodic Averages.

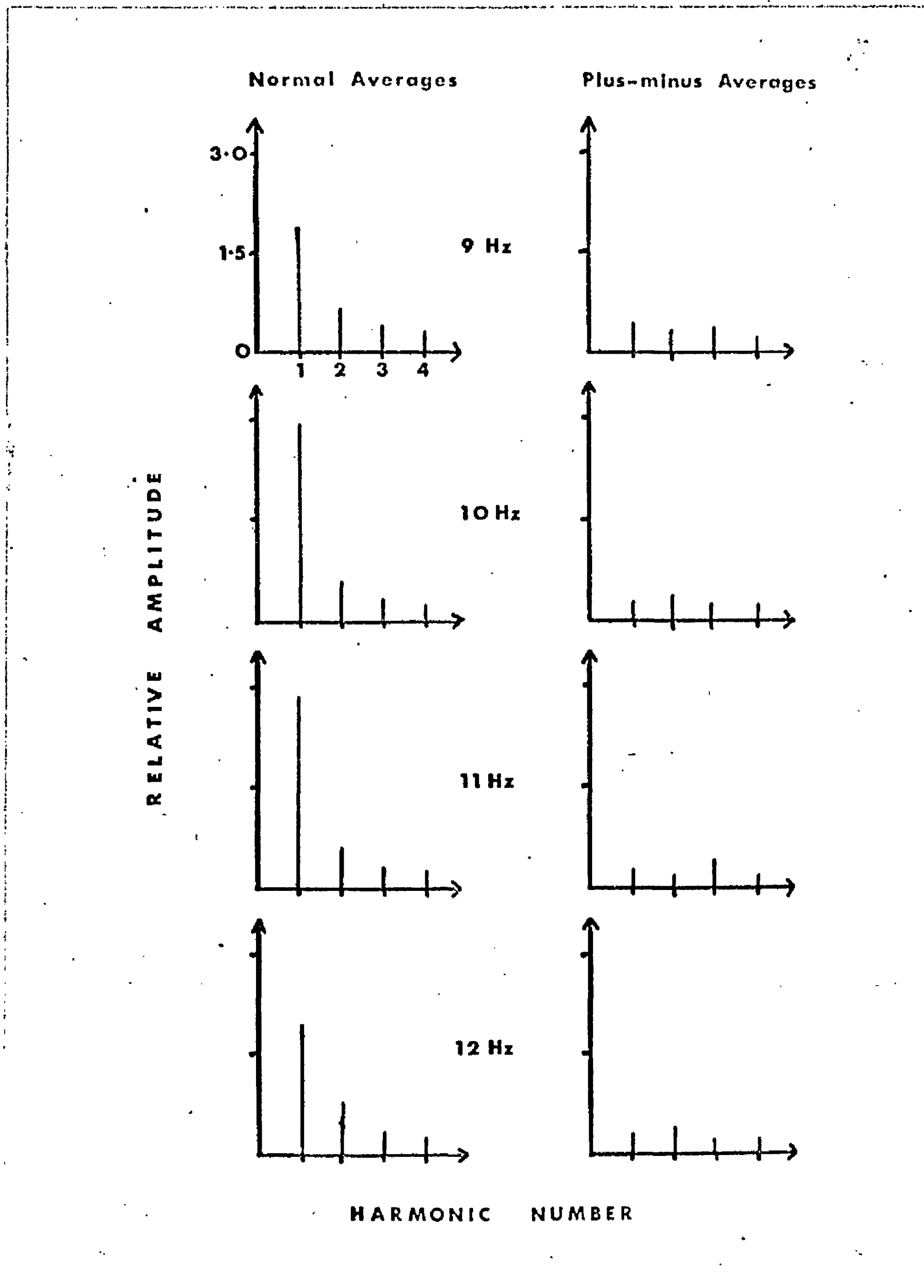


Figure 2.5 Examples of the harmonic components in the periodic averages.

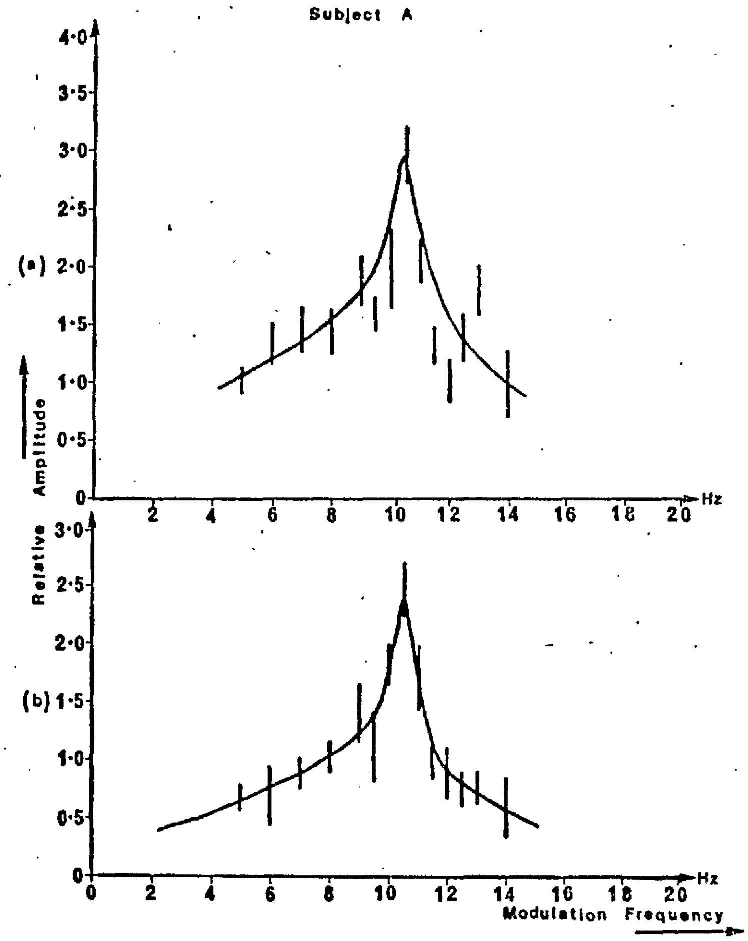


Figure 2.6 Variation with Modulation Frequency of the First Harmonic Amplitude for (a) the uncorrected spectra, and (b) the corrected spectra.

result of some equipment, or other artefact. The sound reduced room used for the experiments is not electrically shielded so there exists the possibility that the potentials could be produced by spurious electric pick-up. Also vibrations of even theoretically non-polarisable electrodes have been known to induce spurious signals.

To test for any artefact, a dummy head was constructed from plaster-of-paris. Electrodes were placed on the skull and connected in a triangle with 5 Kohm resistors to mimic typical values achieved in practice. Headphones were fitted and the skull stimulated at various modulation frequencies with a stimulus intensity of 110 dB H.T.L. This was the maximum available from the audiometer and was chosen as the worst possible case of interference from either electrical or vibrational sources. The averages were constructed as previously described and no signal was visible at the frequency of modulation.

Further tests were performed on a volunteer subject with total bilateral hearing loss. The normal averages and plus-minus averages were again constructed and no significant difference between the two was found for all the modulation frequencies. This experiment also demonstrates that the plus-minus average is a reasonable measure of the noise present in a normal average; in a situation where no signal component is present, the two averages give statistically similar results.

These experiments indicate that the potentials found are due to electrical activity associated with a functioning auditory system and not the result of interference in the instrumentation.

CHAPTER 3

Steady State Potentials and Amplitude Modulation

Stimulus Parameters

3.1 Introduction

This chapter describes the effect of stimulus parameters relevant to audiological assessment on steady state potentials elicited by a sinusoidally amplitude modulated stimulus. A group of six normal hearing adults and two children, aged 6 and 11 years, were investigated over a period of eight months. Each subject underwent at least five experimental sessions, not less than two weeks apart. A further four children, aged between two and five years, participated in limited studies to determine the differences between the response behaviour for adults and children.

3.2 Preliminary results

Some examples of responses have been shown in Chapter 2 for purposes of illustration. Preliminary experiments indicated that, as with using visual stimulation (41), maximal responses are obtained in the region of modulation frequency between 5 Hz and 15 Hz. It is also found that, as most of the response is concentrated in the first two or three harmonics of the Fourier description, it is reasonable to describe the response wave forms in terms of their sinusoidal components. It must be stressed however that there is no a priori reason that the response should in fact be a series of sinusoids, as any periodic waveform may be thus described. As the early harmonics of the response dominate, the bandwidth of the EEG was reduced from 3.2 Hz → 64 Hz to 3.2 Hz → 32 Hz. For normal hearing subjects no differences were found between monaural and binaural stimulation, and all experiments reported in this chapter were performed using binaural stimulation. Preliminary results indicate that the response waveform (that is the amplitude and phase of the Fourier components) is dependent on (a) the frequency of modulation

(b) the modulation depth

(c) the carrier frequency

(d) the number of samples, N, used to compile the average, and

(e) the intensity of the sound stimulus.

For the eight principal subjects experiments are performed in which

(a) the frequency of modulation is varied between 5 Hz and 15 Hz,

(b) the modulation depth is varied from 0% to 100%,

(c) the carrier frequency is varied from 500 Hz to 4000 Hz,

(d) the number of sweeps N is varied from 100 to 5000,

(e) the peak intensity of the stimulus is varied from behavioural threshold to 80 dB HTL.

3.3 Effect of Modulation Frequency

The modulation depth is set at 50%, (Section 3.4), the carrier frequency at 1000 Hz and the peak intensity at 70 dB for all the experiments in this section. The number of samples in each of the averages is 1024. There are found to be large and consistent inter-subject differences in the relation between the response and the modulation frequency. The results are therefore presented separately for each subject and the differences and similarities summarised at the end of the section.

(i) Subject A.

This subject is one of the normal hearing adults and Fig. 3.1 shows the variation with modulation frequency of (a) the amplitude of the corrected first harmonic; (b) the amplitude of the corrected second harmonic and (c) the phase of the first harmonic.

The higher harmonic components of the response waveform were not present to a significant degree.

The amplitude of the first harmonic is sharply dependent on the modulation frequency with a maximum response of about 2.5 μV around 10.5 Hz.

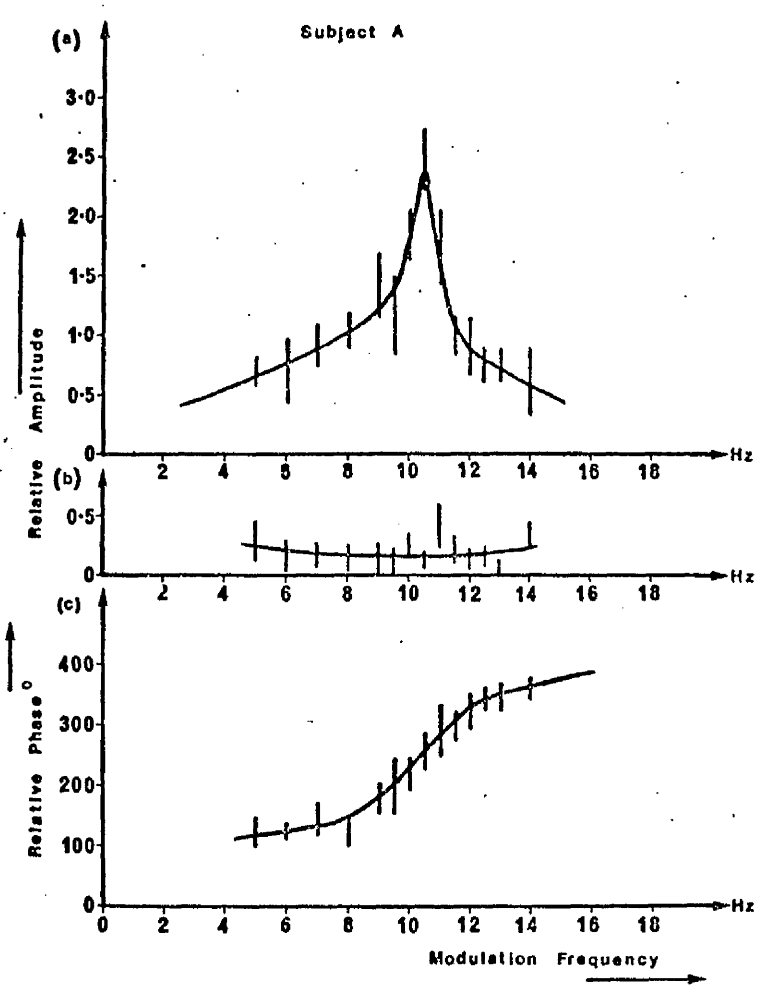


Figure 3.1 Variation with Modulation Frequency of (a) the Corrected First Harmonic, (b) the Corrected Second Harmonic, and (c) the phase of the First Harmonic for Subject A.

There is very little second harmonic present and it exhibits no clear dependence with the frequency of modulation. The phase of the first harmonic changes slowly with modulation frequency except near the region of maximal response where it exhibits a rapid phase change of about 180^{o}. These characteristics are almost identical to those reported using visual stimulation. The means and standard deviations shown in Fig. 3.1 are constructed from six experimental sessions, and clearly indicate the stability of the response behaviour within the subject.

It has already been illustrated (see Chapter 2) how the simple correction applied, smooths the form of the amplitude characteristic. (Fig. 2.6).

(ii) Subject B.

This subject is also an adult, and Fig. 3.2 shows the variation with modulation frequency of (a) the amplitude of the correction applied to the first harmonic, (that is, the first harmonic of the plus-minus average); (b) the amplitude of the corrected first harmonic and (c) the amplitude of the corrected second harmonic. For reasons of brevity these three variations will be referred to as "amplitude characteristics", A, B and C respectively. The results are compiled from a series of five experimental sessions.

Again the first harmonic is the principal component, although on this occasion it's maximum is 1.5 μV with a centre frequency of 9 Hz. The proportion of the second harmonic is about 25% at 9 Hz and tends to decrease with an increase in modulation frequency. It should be noted that owing to the smaller amplitude of the response the correction applied is correspondingly larger in relation to the response and even at 9 Hz (the maximal response) is of the order of 30%. This may be important when the response is used for threshold determination. As with Subject A, the response characteristics are stable with time, and a similar phase characteristic is observed.

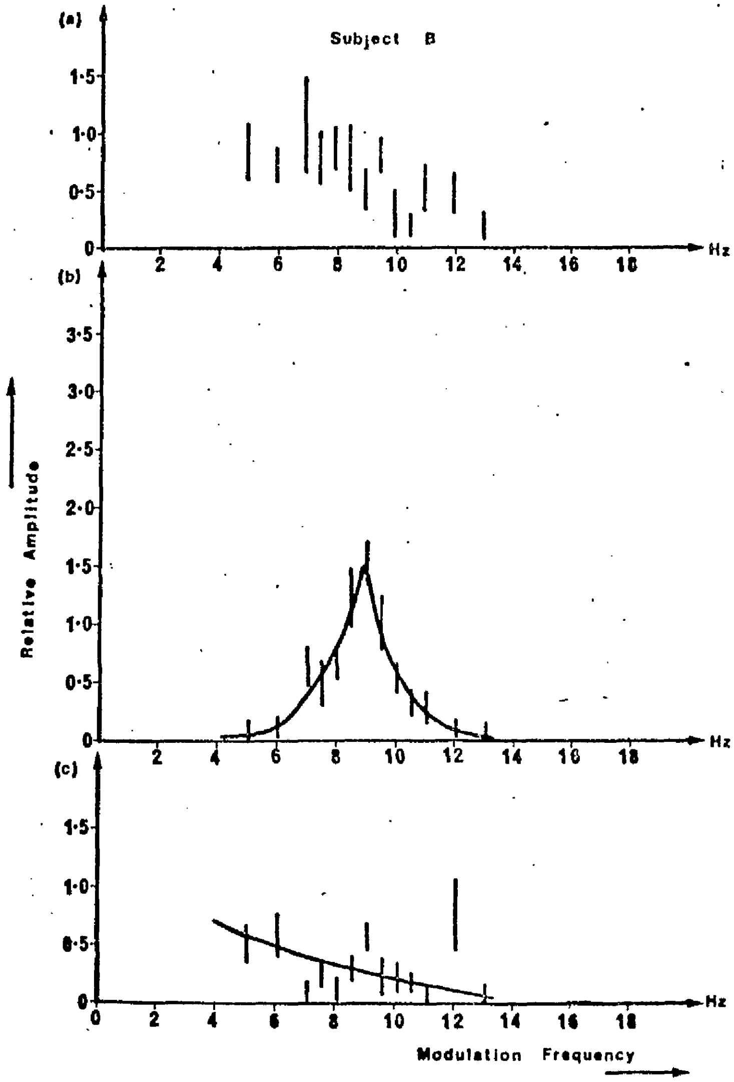


Figure 3.2 Variation with Modulation Frequency of (a) the correction applied to the first harmonic, (b) the corrected first harmonic, and (c) the corrected second harmonic for Subject B.

(iii) Subject C.

This subject is aged 6 years and the amplitude characteristics A, B and C described for Subject B are shown in Fig. 3.3. The first harmonic exhibits a peak response at 12 Hz with a maximum amplitude of 3.5 μV. The width of the amplitude characteristic is significantly larger than for the two previous subjects, with a significant response obtainable at all modulation frequencies between 8 Hz and 14 Hz.

There is an appreciable amount of the second harmonic present in the response, which at 12 Hz is approximately 45% of the first harmonic. Also the form of the second harmonic characteristic tends to follow that of the first harmonic. There was no evidence of third or higher harmonic components. As before, the characteristics are stable within the subject and a phase change similar to that described for Subject A is observed. In this subject the correction applied to the first harmonic (characteristic A) is small relative to the amplitude of the first harmonic, and as previously, does not seem to depend on the amplitude of the elicited response.

(iv) Subject D.

Subject D is a normal hearing adult and the amplitude characteristics A (the correction applied to the first harmonic) and B (the corrected first harmonic), and C (the corrected second harmonic) are shown in Fig. 3.4. Two regions of response, which are sharply frequency dependent, are apparent, centred around 7 Hz and 14 Hz. The response at 7 Hz is approximately 2 μV and at 14 Hz is 1 μV.

The correction applied to the first harmonic is of similar magnitude to the corrected value in the higher region of response with modulation frequency. Clearly the lower response region at around 7 Hz would be used in any audiometric assessment.

The second harmonic component is clearly present and mimics the behaviour of the first harmonic, with two response regions. The response characteristics are however relatively less sharp with modulation frequency

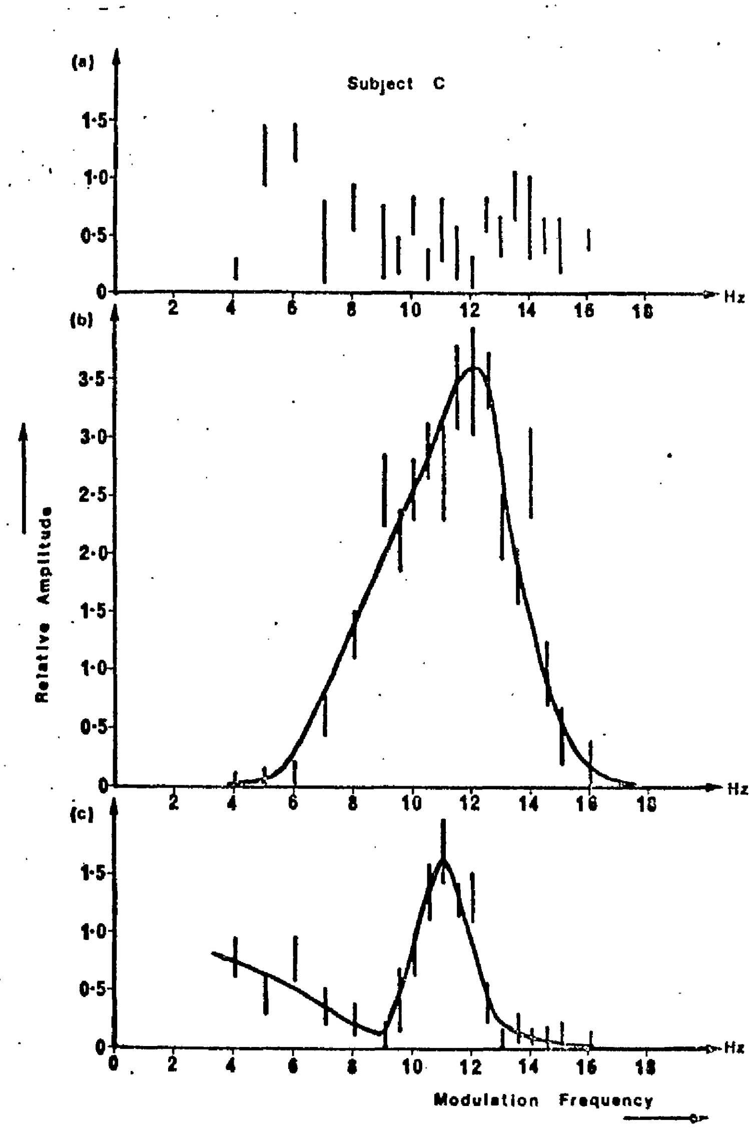
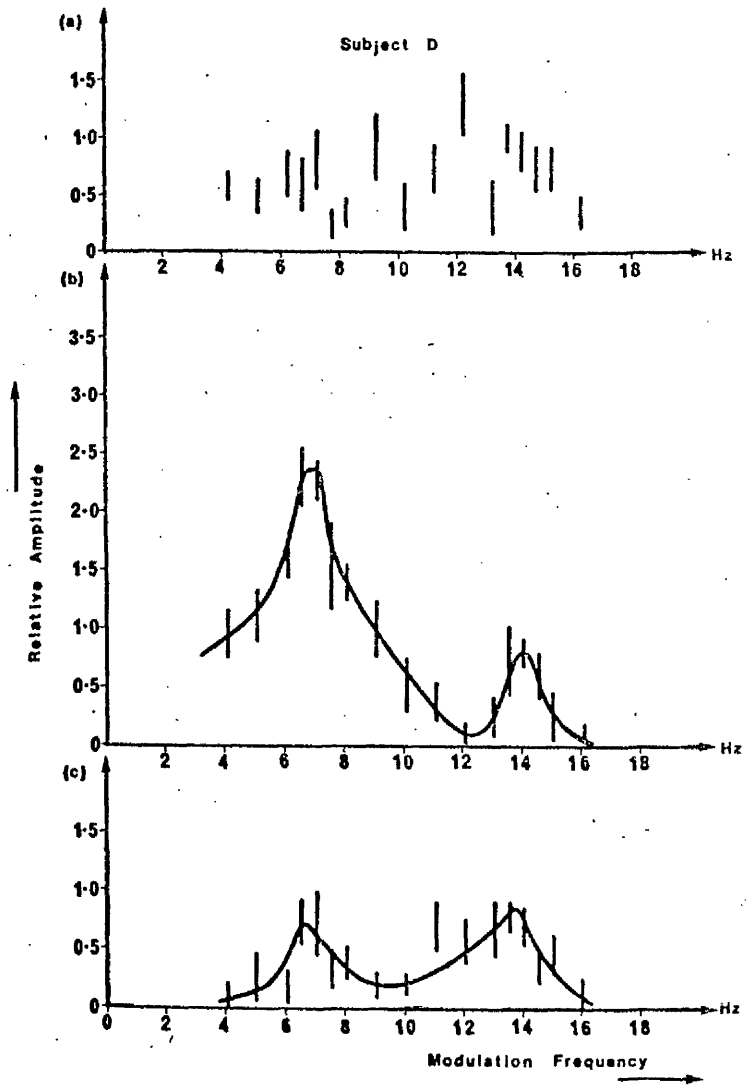


Figure 3.3 Variation with Modulation Frequency of (a) the correction applied to the first harmonic, (b) the corrected first harmonic, and (c) the corrected second harmonic for Subject C.



<u>Figure 3.4</u> Variation with Modulation Frequency of (a) the correction applied to the first harmonic, (b) the corrected first harmonic, and (c) the corrected second harmonic, for Subject D.

and the amplitude of the two peaks are of similar magnitude.

A plot of the phase of the first harmonic as a function of modulation frequency is shown in Fig. 3.5 for this subject. This exhibits a phase of 180° around each of the regions of response and indicates that the two response regions are each behaving in a similar way to the single regions reported for Subjects A, B and C. As in all the previous subjects, the response characteristics with modulation frequency are stable over a series of experimental sessions.

(v) Subject E.

Fig. 3.6 shows the amplitude characteristics A, B and C (described previously) for Subject E, a normal hearing adult. There are two distinct regions of response in the modulation frequency domain for the first harmonic, both of which are very sharply dependent on the modulation frequency. The two maxima are 3 μV and 2 μV respectively.

The correction applied to the first harmonic (amplitude characteristic A) is larger in the region between the two response peaks, and it is clear that if the correction were not applied, the separation between the two response regions would not be achieved so easily.

There is very little second (or higher) harmonic component present and it exhibits no distinctive variation with the modulation frequency.

Other features of the response characteristics for this subject are the same as for Subject D, in that the characteristics are stable over a period of time, and a double phase is found around each of the regions of response in the modulation frequency domain.

(vi) Subject F.

This subject is an 11 year old normal hearing child, whose amplitude characteristics A, B and C as a function of modulation frequency are shown in Fig. 3.7. As with Subjects D and E, there are two regions of response in the amplitude characteristic (A) of the first harmonic. They are maximal

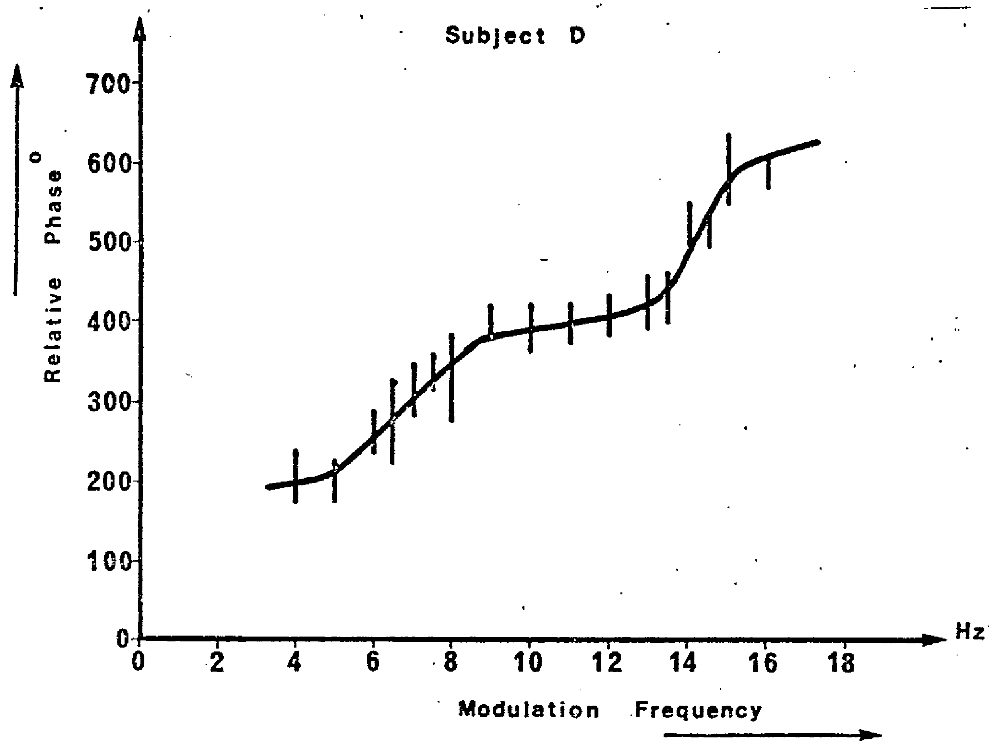


Figure 3.5 Variation with Modulation Frequency of the phase of the first harmonic for Subject D.

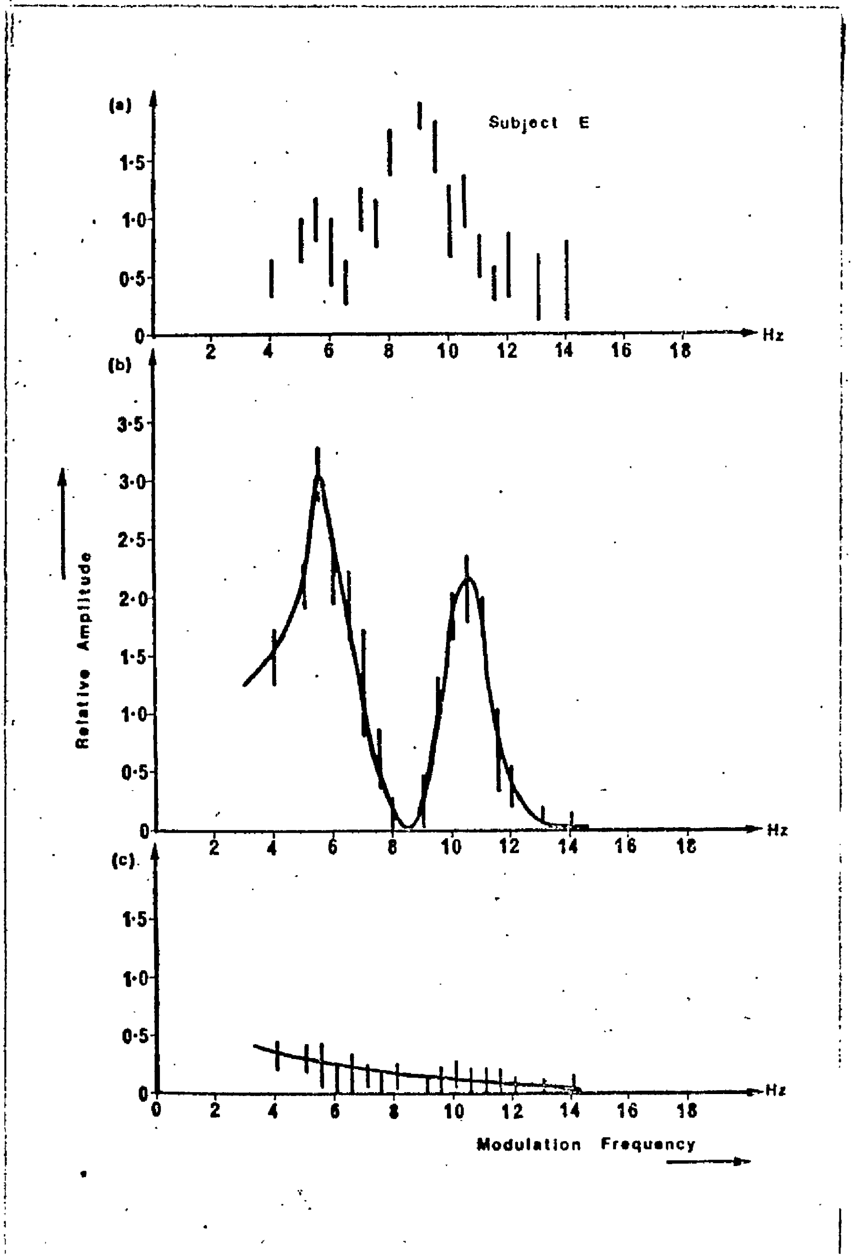


Figure 3.6 Variation with Modulation Frequency of (a) the correction applied to the first harmonic, (b) the corrected first harmonic, and (c) the corrected second harmonic, for Subject E.

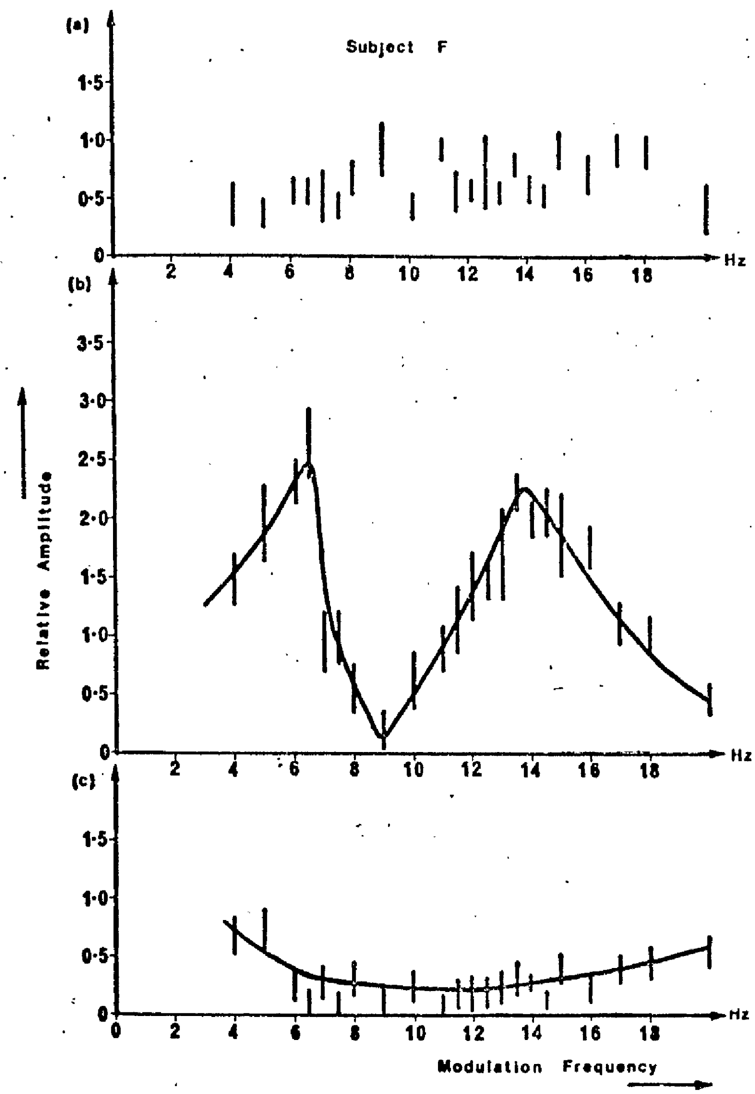


Figure 3.7 Variation with Modulation Frequency of (a) the correction applied to the first harmonic, (b) the corrected first harmonic, and (c) the corrected second harmonic, for Subject F.

at modulation frequencies of 6.5 Hz and 13.5 Hz, with amplitudes of 2.5 μV and 2 μV. The dependence on modulation frequency is much less sharp than for Subjects D and E giving a much wider response characteristic around each of the peaks.

The contribution from the second harmonic, (amplitude characteristic C), is relatively small, while the correction applied to the first harmonic (amplitude characteristic A) shows no consistent dependence on the frequency of modulation.

(vii) <u>Subject G.</u>

The previously defined amplitude characteristics A, B and C for Subject G, a normal hearing adult, are shown in Fig. 3.8. The first harmonic exhibits two regions of response centred on modulation frequencies of 8 Hz and 12.5 Hz with maximum amplitudes of 1.5 μV and 3.3 μV. The response region around 12.5 Hz clearly dominates the characteristic and would be chosen for use in any audiometric assessment. There is an appreciable component of second harmonic present whose variation with modulation frequency mimics that of the first harmonic.

(viii) <u>Subject H.</u>

Fig. 3.9 shows the amplitude characteristics for Subject H, a normal hearing adult. The first harmonic exhibits a sharply frequency dependent maximum around 8 Hz, and as with the previous subject the second harmonic component has a similar variation with modulation frequency. Modulation frequencies below 4 Hz were not employed as at these frequencies the description of the response as "steady-state" is not realistic.

It is clear from the above that there are large inter - subject differences in the effect of modulation frequency onsteady state responses elicited by amplitude modulated stimulation. There are however certain basic similarities in the reaction of different subjects. These are:-

(a) For each subject the response characteristic with

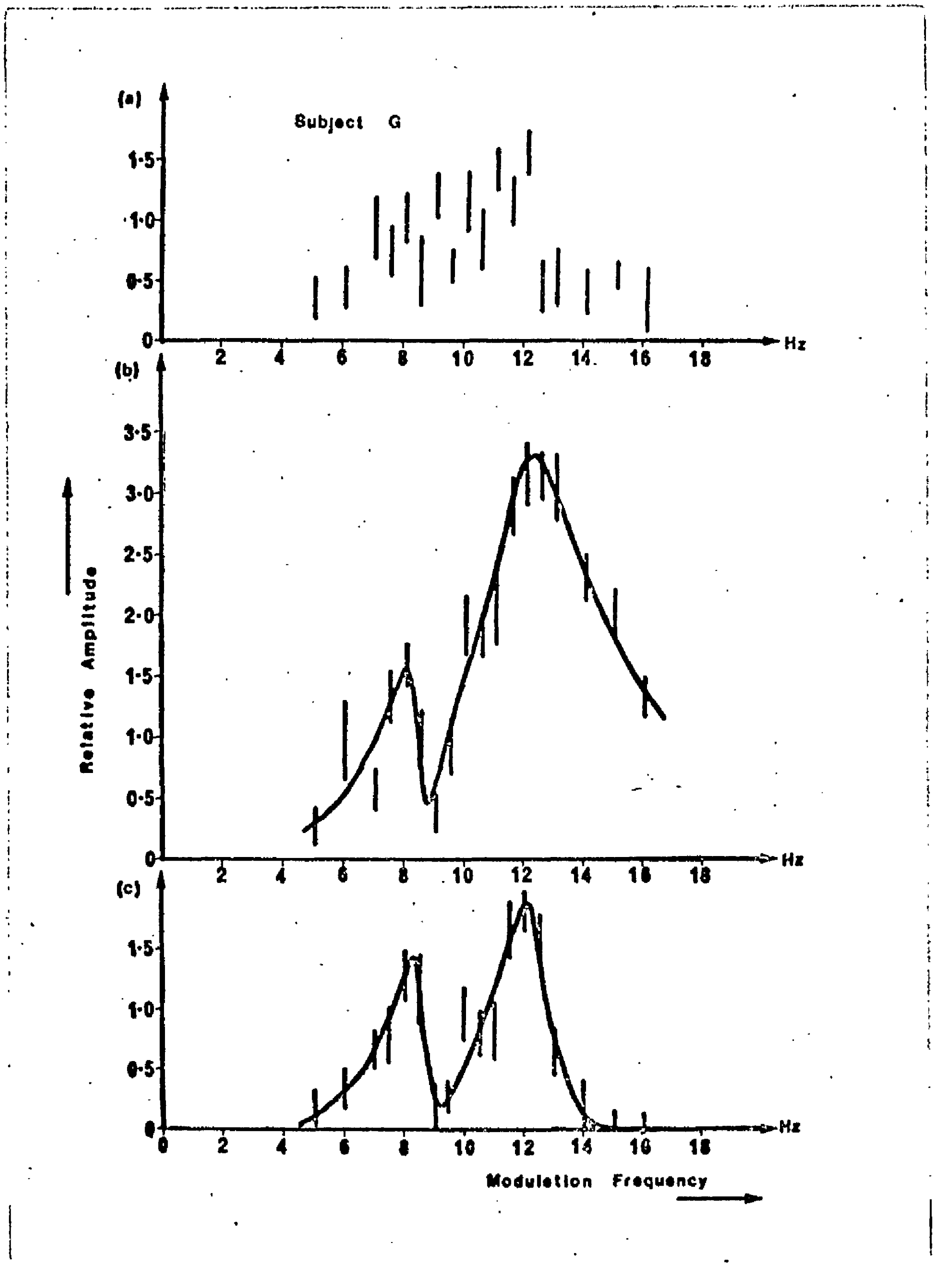


Figure 3.8 Variation with Modulation Frequency of (a) the correction applied to the first harmonic, (b) the corrected first harmonic, and (c) the corrected second harmonic, for Subject G.

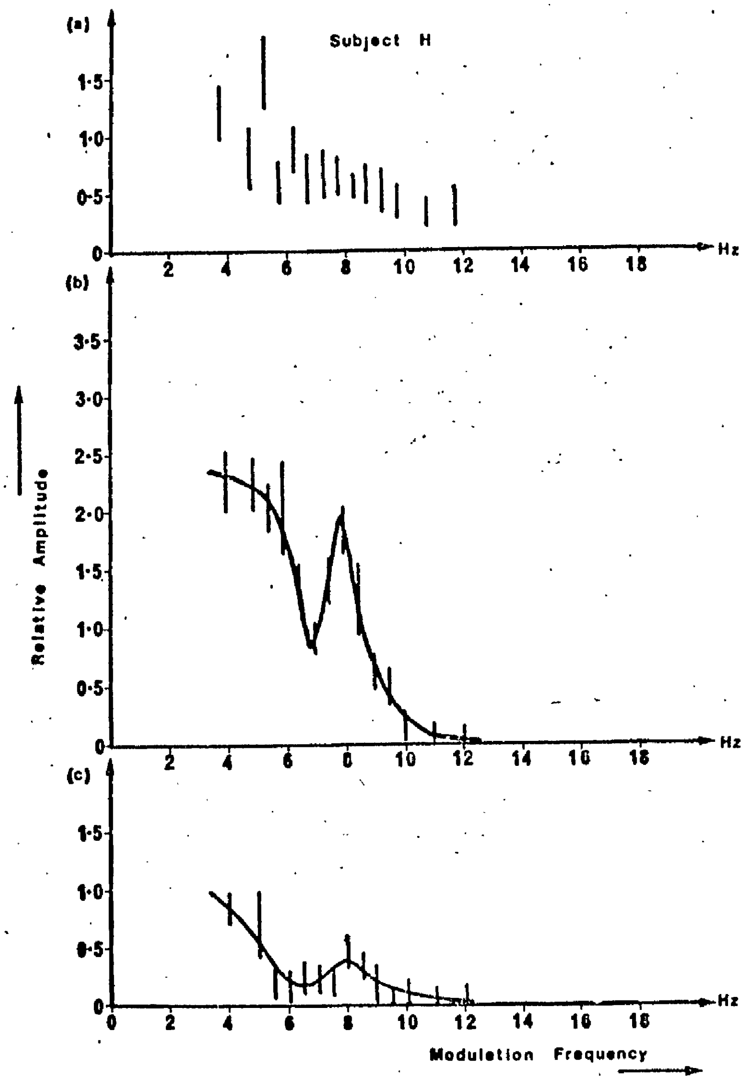


Figure 3.9 Variation with Modulation Frequency of (a) the correction applied to the first harmonic, (b) the corrected first harmonic, and (c) the corrected second harmonic, for Subject H.

respect to modulation frequency is stable in time.

Each of the characteristics described above is derived from at least four recording sessions not less than two weeks apart.

(b) Whenever a peak occurs in the amplitude characteristic for the first harmonic there exists a phase change of 180° in the phase characteristic of that harmonic. This occurred independently of the number of peaks in the amplitude characteristic.

(c) For each subject there exists at least one area of response for modulation frequencies between 5 Hz and 15 Hz.

(d) For each subject the first harmonic is to a greater or lesser degree the predominant component. The third and higher harmonics are present to only a very small degree.

A summary of some of the different parameters for the amplitude characteristic of the corrected first and second harmonics is shown in Tables 3.I and 3.II. Table 3.I shows:-

(a) the number of peaks present

(b) the centre frequencies

(c) the maximum amplitudes

(d) the width in Hz at half the peak height for the first harmonic.

It may be seen that the modulation frequency at which a maximum response is elicited can range from 5.5 Hz (Subject E) to 12.5 Hz (Subjects C and F). Subsidiary response peaks may be found as high at 14.0 Hz (Subject D). The maximum amplitude of the response may range from 1.5 μV (Subject B) to 3.5 μV (Subject C). In the cases where more than one region of response in the modulation frequency domain is present, the lower frequency peak may dominate (Subjects D and E), the two peaks may be of comparable amplitude (Subject F), or the higher frequency peak may dominate (Subject G). A measure of the sharpness of the frequency dependence of the characteristic is the width of the peak at half height, (F.W.H.M. - full width half maximum).

SUBJECT	NUMBER OF PEAKS	CENTRE FREQUENCY Hz	AMPLITUDE μV	F.W.H.M. Hz	CENTRE FREQUENCY Hz	AMPLITUDE μV	F.W.H.M. Hz
A Adult	1	10.5	2.5	2.0	-	-	-
B Adult	1	9.0	1.5	1.5	-	-	-
C Child	1	12.5	3.5	5.1	-	-	-
D Adult	2	7.0	2.3	3.2	14.0	0.7	2.3
E Adult	2	5.5	3.0	2.5	11.0	2.0	2.0
F Child	2	6.5	2.4	3.8	13.5	2.2	5.1
G Adult	2	8.0	1.5	1.5	12.5	3.3	4.5
H Adult	1	8.0	1.9	1.1	-	-	-

TABLE 3.I. Parameters of the corrected first harmonic for the principal subjects.

(F.W.H.M. = Full Width Half Maximum).

SUBJECT	NUMBER OF PEAKS	CENTRE FREQUENCY Hz	$\frac{F_2}{F_1} \times 100\%$	F.W.H.M. Hz	CENTRE FREQUENCY Hz	$\frac{F_2}{F_1} \times 100\%$	F.W.H.M. Hz
A Adult	0	-	0.7	-	-	-	-
B Adult	0	-	17	-	-	-	-
C Child	1	11.0	47	2.2	-	-	-
D Adult	2	6.5	31	2.0	13.5	100	2.3
E Adult	0	-	9	-	-	5	-
F Child	0	-	13	-	-	11	-
G Adult	2	8.0	91	1.9	12.5	56	2.1
H Adult	1	8.0	20	-	-	-	-

TABLE 3.II. Parameters of the corrected second harmonic for the principal subjects.

Table 3.I indicates that there are large differences in this sharpness with the F.W.H.M. varying from 1.1 Hz (Subject H) to 5.1 Hz (Subject C). Of the two small children used as subjects, one exhibits a single response region with modulation frequency and the other two peaks. In both children the maximum amplitudes are relatively large (3.5 μV and 2.4 μV) and the response regions relatively wide in the frequency domain (with F.W.H.M. of 5.1 Hz and 3.8 Hz).

Table 3.II shows some parameters of the amplitude characteristic of the corrected second harmonic, with (a) the number of peaks present; (b) the centre frequency of each peak; (c) the ratio of the second harmonic to the first harmonic as a percentage at each peak in the first harmonic, and (d) the width at half height of each peak.

The table indicates that for four subjects (A,B,E,F) no peaks are present in the second harmonic, for two subjects (C, H) one peak is present, and for two subjects (D, G) two peaks are present. Where there are peaks present in the second harmonic they are centred around the same frequencies as peaks in the first harmonic. In subjects (A,B,E,F) where the second harmonic shows no characteristic variation with modulation frequency, the second harmonic ranges from 5% to 17% of the peak first harmonic. In the other subjects this percentage ranges from 20% to 100%. The relationship between the variation with modulation frequency for the first and second harmonic is further investigated by taking a linear correlation between the first and second harmonic. The amplitude of the first harmonic is plotted against the amplitude of the second harmonic and the resultant correlation coefficient for each subject is shown in Table 3.III. The low correlation coefficients for subjects A, B, E and F indicate that the amplitude characteristics of the first and second harmonics are not related. The converse applies for subjects C, D, G and H.

Similarly the relationship between the first harmonic, of the normal average and the first harmonic of the plus-minus average is investigated

SUBJECT	CORRELATION COEFFICIENT
A	0.12
B	0.09
C	0.77
D	0.63
E	0.17
F	0.07
G	0.91
H	0.88

TABLE 3.III.

Correlation between the corrected first harmonic and the corrected second harmonic for the principal subjects.

and the relevant correlation coefficients are shown in Table 3.IV. These correlation coefficients indicate no significant relationship between the amplitude characteristic for the first harmonic and the correction applied to it to account for residual EEG activity.

3.4 Effect of Modulation Depth

The modulation depth of the stimulus as defined in Fig. 3.10 may be varied between zero and 100%. At zero modulation depth no response would be expected as the stimulus is then simply a continuous tone of constant intensity. This was confirmed in four of the subjects (A, B, D, H) prior to investigating the effect of different modulation depths on the response. In these four subjects no significant difference was found between the normal average and the plus-minus average over a series of five recordings for each subject. This indicates that no response is in fact present at zero modulation depth.

Experiments were then performed on each of the eight principal subjects in which the modulation depth is varied between zero and 100%. For each of the subjects the carrier frequency is 1000 Hz, the peak intensity is 70 dB HTL, and the number of samples in each average is 1024. Also the modulation frequency is set for each subject so that a maximum response is obtained, as determined from the results of the previous section. These optimal conditions are given in Table 3.V. Three experiments are performed for each subject and the results subjected to the harmonic analysis described previously. Fig. 3.11 shows the means of the amplitude of the first harmonic component for each subject. The phase of the first harmonic (and in fact all higher harmonics) was found to be independent of modulation depth for all subjects. The variation of the first harmonic amplitude exhibits little inter-subject difference as a function of modulation depth, and this is also the case for the higher harmonics. The results have been plotted in terms of percentage of maximum amplitude achieved in order to

SUBJECT	CORRELATION COEFFICIENT
A	0.18
B	0.13
C	0.04
D	0.22
E	0.29
F	0.11
G	0.17
H	0.18

TABLE 3.IV.

Correlation between the first harmonic of the normal average and the first harmonic of the plus-minus average for the principal subjects.

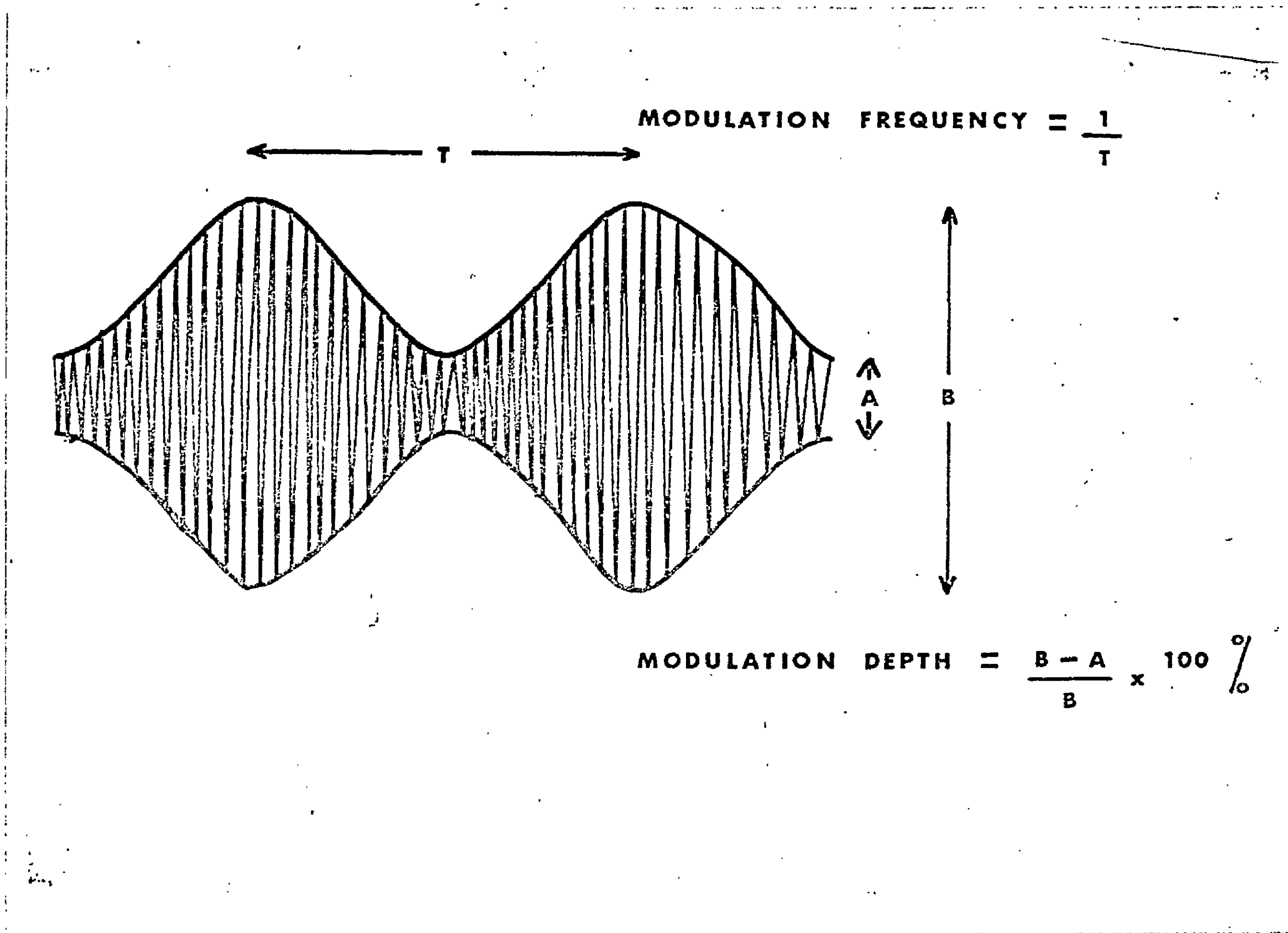


Figure 3.10 Definition of Modulation Depth.

SUBJECT	MODULATION FREQUENCY Hz
A	10.5
B	9.0
C	12.5
D	7.0
E	5.5
F	6.5
G	12.5
H	8.0

TABLE 3.V.

Optimal modulation frequencies for the eight principal subjects.

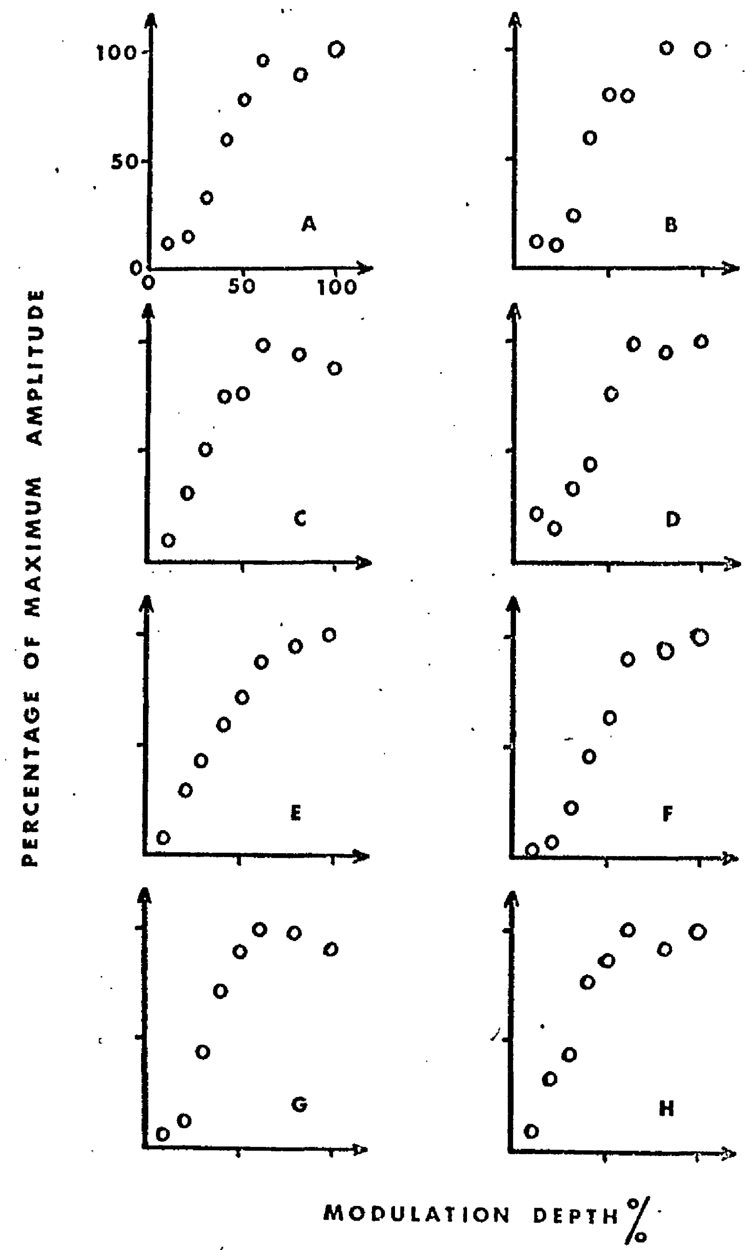


Figure 3.11 Amplitude of the corrected first harmonic as a function of modulation depth for the principal subjects.

facilitate inter-subject comparison and because the different subjects have different absolute response magnitudes. The results from the eight subjects for the first and second harmonic amplitudes are grouped together and are shown in Fig. 3.12. The first harmonic amplitude is seen to saturate at a modulation depth of around 60%, while the second harmonic amplitude increases monotonically up to 100% modulation depth. This result is similar to results reported previously using both visual and auditory stimulation (41, 44). For purposes of audiometric assessment therefore, the optimal modulation depth would be around 50% to 60% giving a minimum of harmonic distortion.

3.5 Effect of Carrier Frequency

If the steady state responses to amplitude modulated stimulation are to be applied to audiology, they must be reliably obtainable throughout the range of auditory frequencies. To test this experiments were performed on the eight principal subjects at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.

The modulation frequencies are optimally set as in the previous section (see Table 3.V), the modulation depth set at 60%, the peak intensity set at 70 dB and the number of samples in each average is 1024.

Fig. 3.13 shows the variation with carrier frequency of the amplitude of the first harmonic for the eight subjects. The inter-subject variation is found to be small, with each subject having a maximum response at the lower frequencies which falls to approximately 50% of the maximum achieved at 4000 Hz. Similar results are found for the amplitude of the second harmonic, while the phase of the first and second harmonics is found to be invariant with carrier frequency. As in the previous section, results have been presented as the percentage of the maximum amplitude achieved for each subject to aid inter-subject comparison. The results for the eight subjects are collected and the

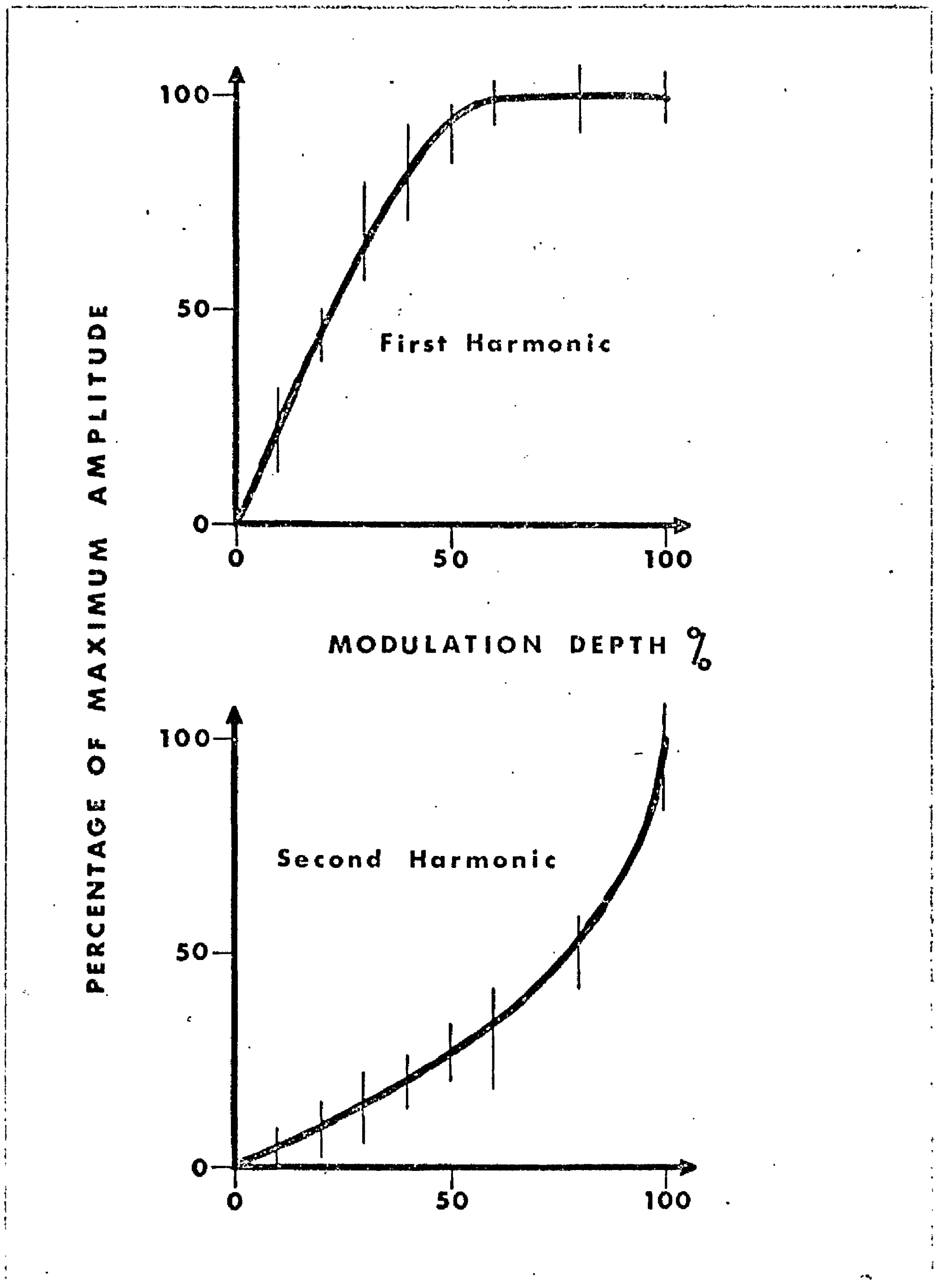


Figure 3.12 Grouped data for the amplitude of the corrected first and second harmonics as a function of modulation depth.

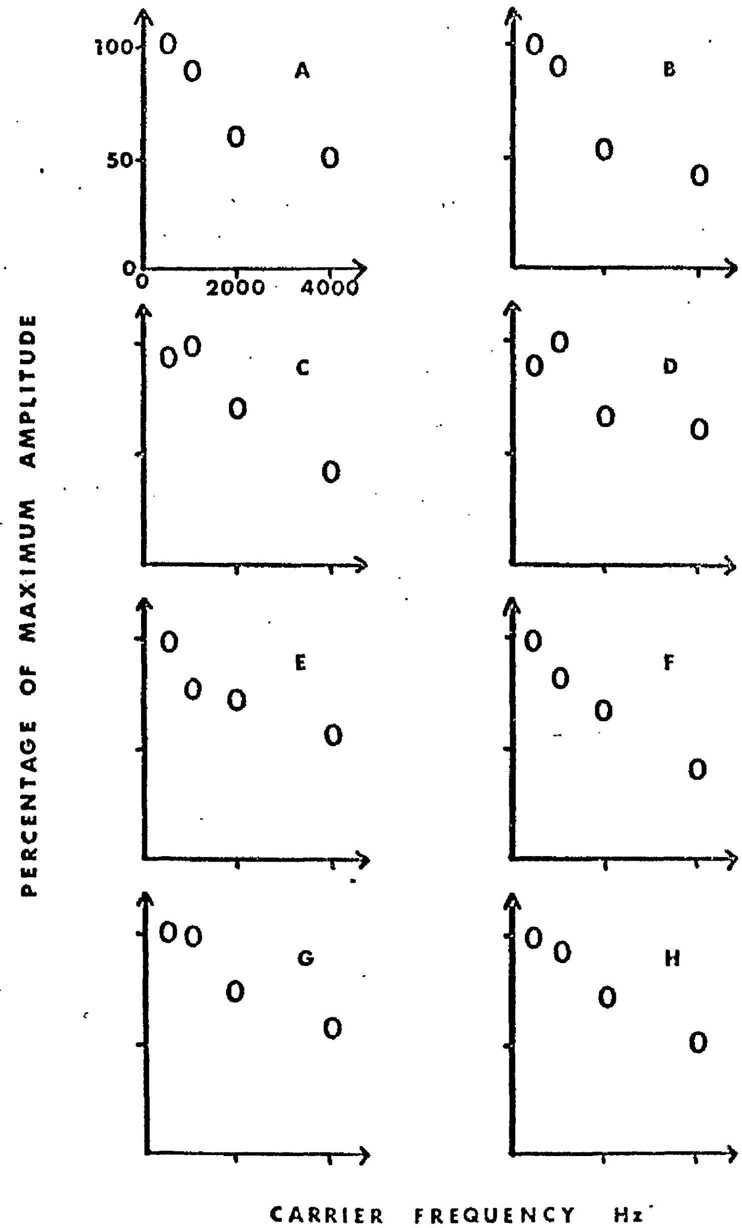


Figure 3.13 Amplitude of the corrected first harmonic as a function of carrier frequency for the principal subjects.

mean magnitudes for the amplitude of the first and second harmonics shown in Fig. 3.14.

3.6 Effect of Number of Samples in the Average

The number of samples used to compile the average may affect the amplitude of the response if the process producing the response fatigues or habituates. The arousal situation is very subjective, and in a first attempt to control subject state the individual sits quietly in comfortable surroundings and reads from material of his or her choice. The effect of subject state will be more closely assessed in Chapter 4, where clinical trials are described.

Recordings are made from each subject using the optimal individual stimulus parameters. The modulation frequencies are given in Table 3.V, the modulation depth is 60%, the carrier frequency is 1000 Hz and the peak intensity is 70 dB HTL. The stimulus is presented to the subject for 5000/F seconds, where F is the modulation frequency in use (i.e. 5000 cycles of the modulated stimulus are presented).

The response is analysed in sections of 100 cycles of the modulation frequency and the amplitude of the first harmonic is calculated as described in Chapter 2. Fig. 3.15 shows the growth and decay of this first harmonic as the number of cycles of modulation increases for Subject A. The amplitude increases rapidly to reach a plateau level which then gradually decreases as the stimulus is further applied.

Three parameters have been chosen to characterise this behaviour, and investigate inter-subject variation and changes with subject state.

They are:-

(a) the start of the plateau

(b) the end of the plateau

(c) the point where the amplitude of the corrected first harmonic has fallen to 50% of its maximum value.

Table 3.VI shows these parameters for each of the eight principal

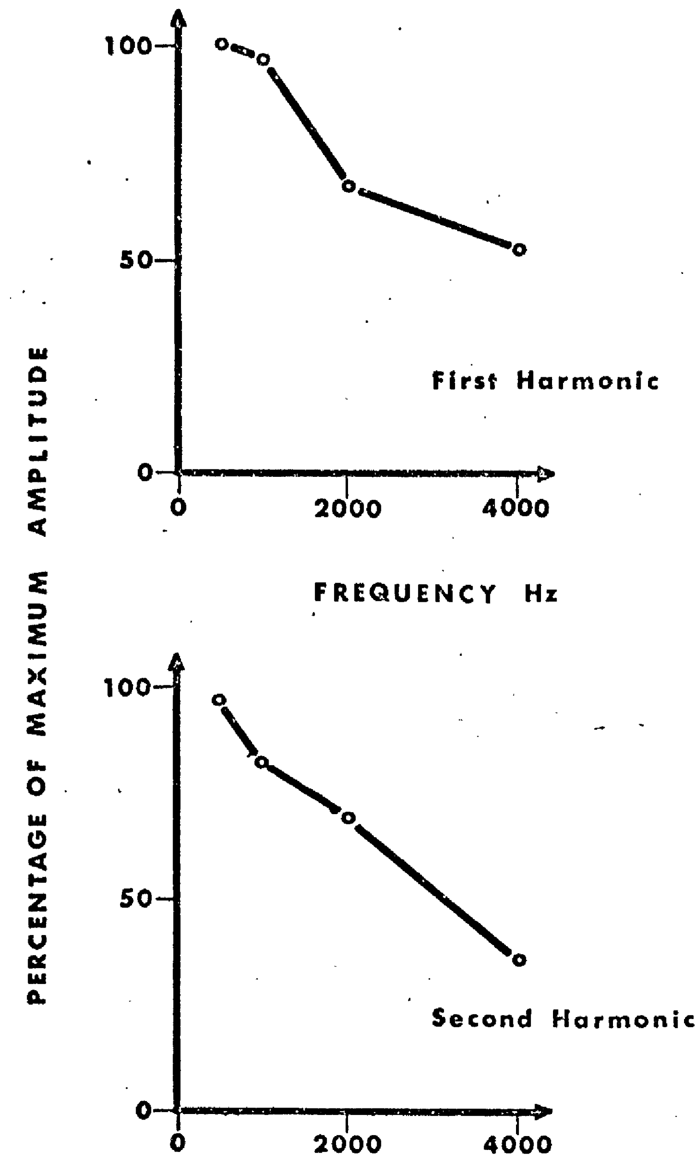


Figure 3.14 Grouped data for the amplitude of the corrected first and second harmonics as a function of carrier frequency.

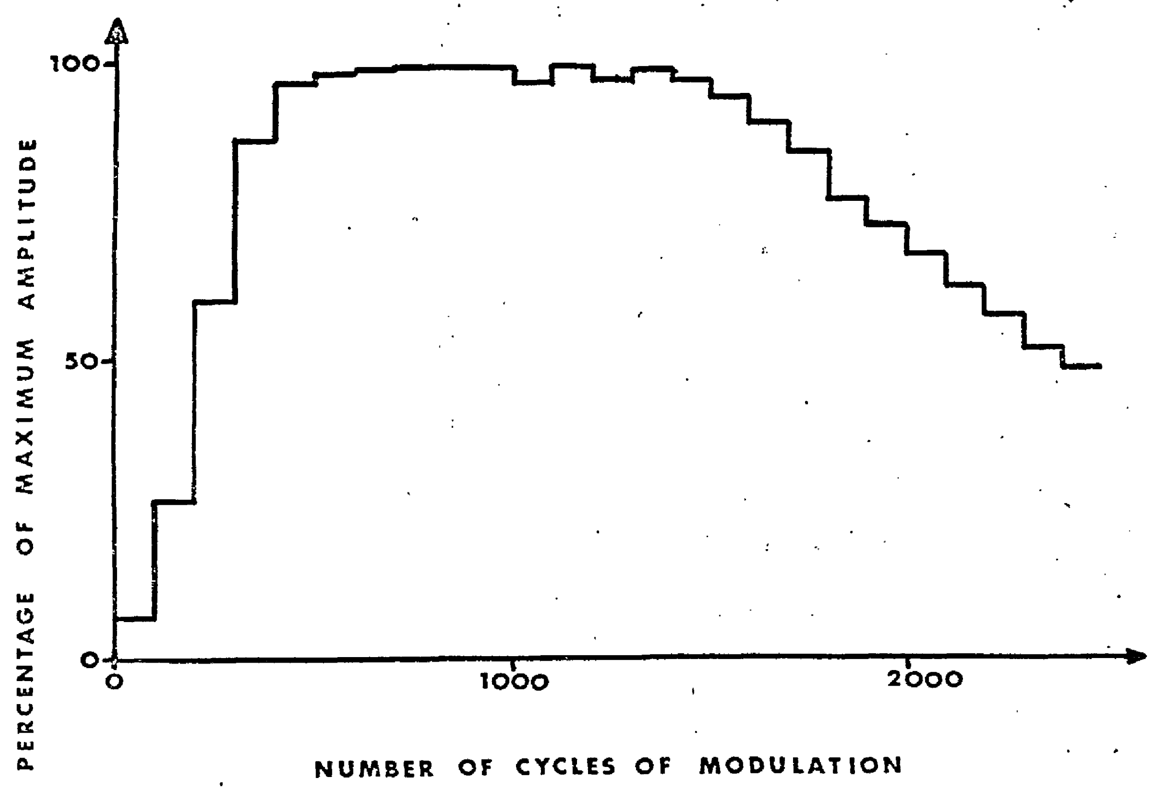


Figure 3.15 Growth and decay of the amplitude of the corrected first harmonic for Subject A.

SUBJECT	PS	PE	P50
A	500	1400	2200
B	400	1800	2600
C	500	1500	2700
D	300	1700	2100
E	300	1700	2100
F	500	1400	2400
G	400	1600	2500
H	400	1600	2300

TABLE 3.VI.

Parameters of response of growth and decay of the corrected first harmonic for the principal subjects. PS - number of cycles to start of platea; PE - number of cycles to end of plateau; P50 - number of cycles to point where response is 50% of maximum.

subjects. The shapes of the curves are very similar, and it can be seen from the table that there is relatively little variation in the parameters for this quietly resting subject state. It is interesting to note that to achieve this agreement between subjects (for whom the modulation frequencies used are different), the data are plotted in terms of cycles of modulation presented, and not absolute time.

It may be seen that a choice of about 1000 as the number of samples N in the average, with the first 500 cycles presented to the subject omitted is reasonable. Thus each stimulus should be presented for 1500/F seconds with the first 500/F seconds ignored, where F Hz is the frequency of modulation.

3.7 Effect of Stimulus Intensity

The potential audiological application of steady state responses is threshold determination. Therefore the variation of the response parameters with stimulus intensity is of fundamental importance, and the whole point of steady state potentials is that it is easier to set up a simple definitive criterion regarding the presence or absence of a response (i.e. the presence or absence of a difference between the normal and plus-minus averages).

The difference in the amplitude of the first harmonic for the normal average and the plus-minus average is investigated as a function of stimulus intensity. The stimulus intensity is calibrated as the peak intensity achieved during the modulation cycle in dB HTL, and is varied from zero to 80 dB HTL for each subject, each in three experimental sessions.

Fig. 3.16 shows the means of the amplitude of the corrected first harmonic for the two types of average for the eight subjects. The normal average amplitude is seen to be greater than that for the plus-minus average until between 10 dB and 20 dB above threshold. All eight subjects exhibit a similar pattern of variation with stimulus

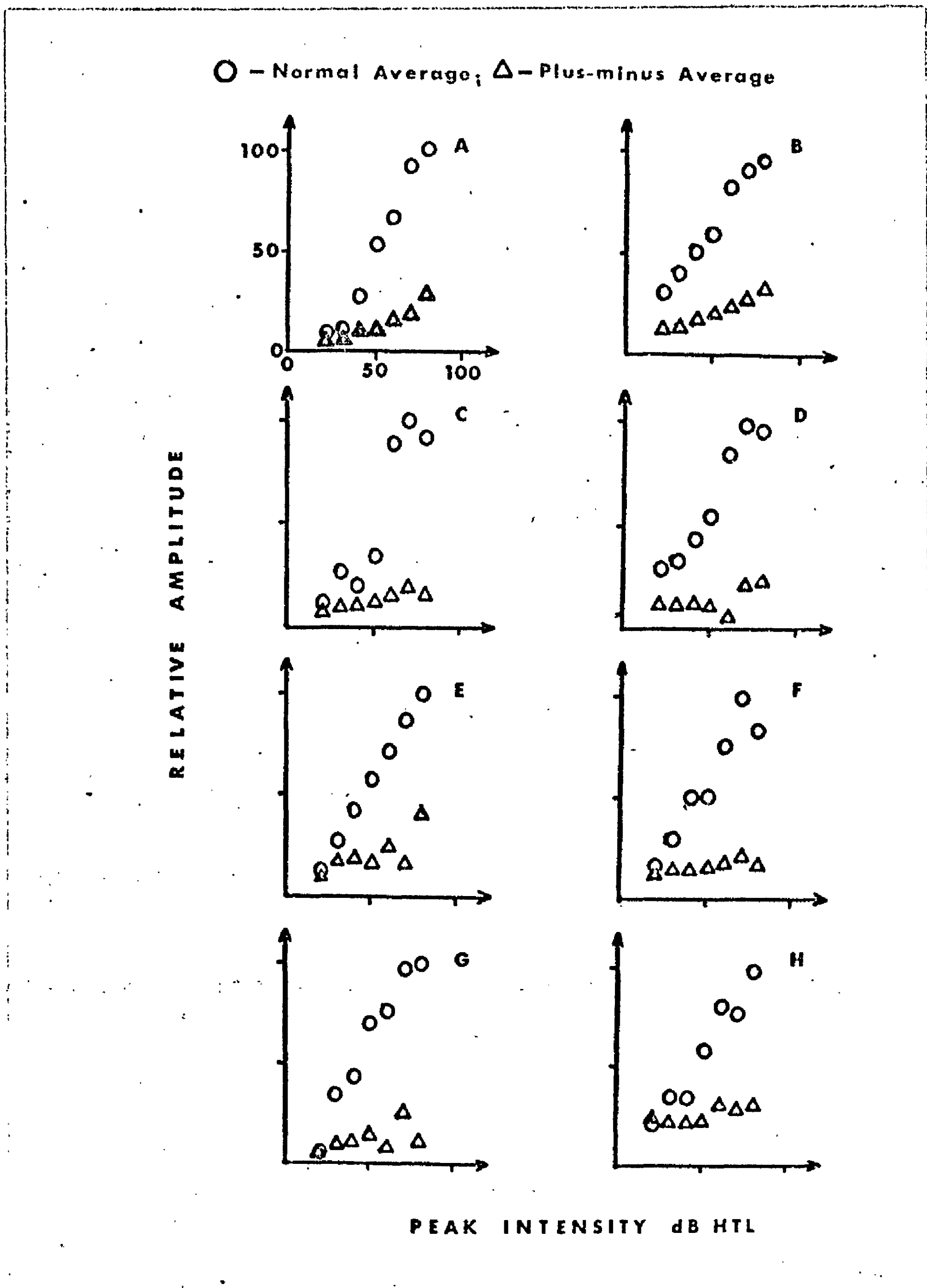


Figure 3.16 Variation with stimulus intensity of the amplitude of the first harmonic for the normal and plus-minus averages for the principal subjects.

intensity and the results are grouped and displayed in Fig. 3.17.

A Student's t-test is performed on the collected data to compare statistically the amplitude of the normal and plus-minus average first harmonics. The resultant coefficients are shown in Table 3.VII. There are statistically significant differences (at the 95% level) between the averages to within 20 dB of threshold, and only at zero and 10 dB HTL is no response detectable by this analysis. Of course this study involves none of the clinical problems likely to be encountered in practice, and the particular one large inter-subject variability of optimal modulation frequency has been demonstrated. An investigation of threshold determination using steady state potentials to amplitude modulation is included in Chapter 4.

3.8 Results from Subsidiary Group of Children

The results presented in the preceding sections are obtained from the principal subject group containing six normal hearing adults and two normal hearing children aged 6 and 11 years. Many potential subjects are aged under 11 years old and further investigation of the response behaviour in young children is performed on a further four children. Subject C1 is aged 2 years, C2 aged 2½ years, C3 aged 4 years and Subject C4 aged 5 years.

This subsidiary group was unable to attend for repeated experimental sessions and therefore inter-subject stability of the response behaviour could not be assessed. The results in this section are obtained from one comprehensive experimental session on each subject and are compared with the more comprehensive data from the principal group of subjects.

(a) Variation with Modulation Frequency

Parameters of the corrected first harmonic amplitude are shown in Table 3.VIII and for the corrected second harmonic amplitude in Table 3.IX. They exhibit a range and variation similar to the principal group of subjects. There is a tendency for the child subject to exhibit a

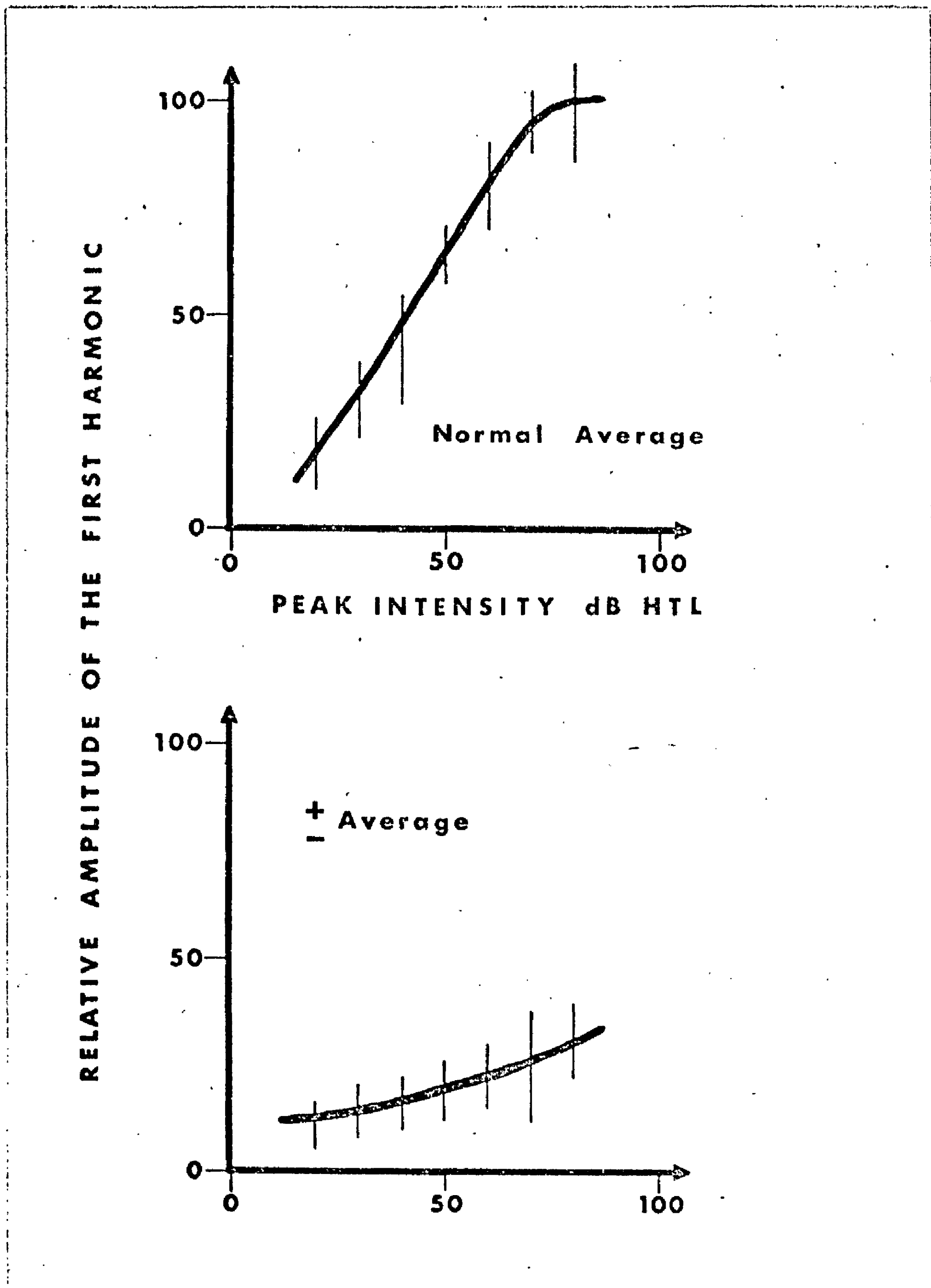


Figure 3.17 Grouped data for the amplitude of the first harmonic for the normal and plus-minus averages as a function of stimulus intensity.

INTENSITY dB HTL	t-value
80	7.82*
70	7.94*
60	5.81*
50	4.60*
40	3.96*
30	3.11*
20	2.38*
10	1.07
0	0.42

TABLE 3.VII

Statistical comparison of normal and plus-minus averages as a function of stimulus intensity for the principal subjects.

* Denotes a significant difference at the 95% level.

No. of Peaks	SUBJECT C1	C2	C3	C4
	1	1	2	2
Centre freq. Hz.	13.0	11.5	7.0	6.0
Amplitude μV	3.1	2.6	1.9	2.6
F.W.H.M. Hz.	2.8	3.1	2.2	4.2
Centre freq. Hz.	-	-	14.0	12.5
Amplitude μV	-	-	3.4	2.3
F.W.H.M. Hz.	-	-	4.2	2.7

TABLE 3.VIII

Parameters of the corrected first harmonic of the subsidiary subjects.

	SUBJECT			
	C1	C2	C3	C4
No. of Peaks	1	1	0	2
Centre freq. Hz.	13.0	11.5	-	6.5
F_2/F_1 x 100%	19	31	14	36
F.W.H.M. Hz.	2.6	2.1	-	3.1
Centre freq. Hz.	-	-	-	12.5
F_2/F_1 x 100%	-	-	21	31
F.W.H.M. Hz.	-	-	-	2.6

TABLE 3.IX

Parameters of the corrected second harmonic for the subsidiary subjects.

large response amplitude and their amplitude characteristic with modulation frequency is relatively wide compared with the adult subjects. In all the cases the phase characteristic varies similarly to the adult subjects and apart from the increased width of the response areas, no consistent deviation from the behaviour described in previous sections is observed.

(b) Variation with Modulation Depth

The four child subjects exhibit the same behaviour as the principal group as the modulation depth is varied between zero and 100%. The first harmonic amplitude increases as the modulation depth is increased, and then saturates at modulation depths above 60%. The second harmonic amplitude continues to increase until 100% modulation depth is reached.

(c) Variation with Carrier Frequency

As the carrier frequency is varied between 500 Hz and 4000 Hz, both the first and second harmonic amplitudes decrease to about 50% of the maximum at the high frequencies. This behaviour is identical to that for the main subject group.

(d) Variation with Number of Samples in the Average

Parameters for the growth and decay of the first harmonic amplitude are shown in Table 3.X. The subject state is more difficult to control with young children, but as far as possible was arranged to be mentally alert but seated quietly. The parameters characterising the growth and decay of the response amplitude are in the same range as for the main group.

(e) Variation with Stimulus Intensity

As in the previous experiment with stimulus intensity, the first harmonic amplitude of the normal average is compared statistically with the first harmonic amplitude of the plus-minus average by a student's t-test to ascertain the presence of a response component. The resultant coefficients are shown in Table 3.XI. A response component is present statistically at 30 dB HTL compared with the 20 dB HTL obtained for the

SUBJECT	PS	PF	P50
C1	400	1600	2900
C2	700	1400	2300
C3	500	1500	2400
C4	400	1500	2300

TABLE 3.X

Parameters of response growth and decay for the subsidiary subjects.

PS - number of cycles to start of plateau

PF - number of cycles to end of plateau

P50 - number of cycles to point where response is 50% of maximum.

INTENSITY dB HTL	t-value
80	9.41*
70	12.68*
60	6.21*
50	4.36*
40	2.91*
30	2.36*
20	1.84
10	0.71
0	0.22

TABLE 3.XI

Statistical comparison of normal and plus-minus averages as a function of stimulus intensity for the subsidiary subjects.

* Denotes a significant difference at the 95% level.

principal subjects.

3.9 Summary

The eight principal subjects have been intensively investigated with respect to the effect on the steady state responses to amplitude modulated stimulation, of

(a) modulation frequency

(b) modulation depth

(c) carrier frequency

(d) number of samples in the average

(e) stimulus intensity

There are large inter-subject differences in the variations with modulation frequency of the first and second harmonic amplitudes, which poses the problem of determining the optimal frequency of modulation for audiological assessment. There are no significant inter-subject differences in the other studies and in all cases there is intra-subject stability. The optimal modulation depth is found to be 60% and 1000 samples are an optimal number of samples to construct the average, if the first 500 cycles of modulation are ignored. The responses are present at the required audiological frequencies and may be shown statistically to be present to within 20 dB of behavioural threshold.

A subsidiary group of four children indicated no significant differences in the behaviour of adult and child responses, apart from a tendency in children for the response regions to be wide in the modulation frequency domain and the response amplitudes large.

CHAPTER 4

Clinical Assessment using Amplitude Modulated Stimulation

4.1 Introduction

This chapter investigates the efficiency with which steady state responses to amplitude modulated stimulation may be used to estimate the behavioural threshold of the stimulus. Optimal stimulus parameters have been determined in the previous chapter, with the exception that the optimum frequency of modulation requires individual determination for each subject. The results quoted previously were all obtained using binaural stimulation from normal hearing adult and child subjects, and therefore the effect of monaural and binaural stimulation for normal and hearing impaired subjects requires investigation. As has been mentioned in Chapter 1, clinical assessment of young children may require sedation, and the effects of the subject state must be known.

With knowledge of the effect of these variables experiments are performed on groups of hearing impaired adults and children to determine the electrophysiological threshold using the analysis described previously. The results are then compared with the electrophysiological threshold obtained using transient stimulation (described in Chapter 1) and the behavioural threshold obtained using conventional audiometry.

4.2 Effect of Subject State

The experiments described in the preceding chapter were all obtained by requiring the subject to sit and read quietly in an attempt to control to some extent the state of the subject. The use of sedation in the electrophysiological assessment of young hyper-active children is standard procedure, and the effects of attention and different sedatives on the averaged EEG response to auditory stimulation have been well documented (27, 28, 29, 30, 31). Before any use is made of steady state potentials, their dependence on subject state must be determined. To this end, a series of experiments are performed in which the subject is pharmacologically induced into different stages of sleep, and the changes in the response parameters are investigated.

Sleep stage zero (S0) is taken to represent the awake state, and the stages of sleep characterised by indices one to four (S1 to S4) in the conventional manner (47). In order to accurately characterise the sleep stage at any given time, the tape recorded EEG was placed into a commercial automatic sleep analyser attached to the computer (48) which characterises each ten second section of EEG activity into the indices S1 to S4. Single cycle and periodic averages are constructed as described in Chapter 2, and an average, for which all the sleep stage indices are identical, is accepted for harmonic analysis. All other response averages are automatically discarded and a new average is begun. Thus each average and its subsequent harmonic analysis is associated with a single index which is used to characterise the sleep stage of the subject.

The experiments were performed, using the optimal stimulus conditions determined in Chapter 3 with a carrier frequency of 1000 Hz, on four of the principal subjects (Subjects A, B, D and H) who were members of hospital staff, and sleep stages were induced under clinical supervision, using doses of nitrazepam. Some experiments were also performed using an approximation to natural sleep, in which the subject remained awake throughout the night and the tests performed the following day.

The effect of different stimulus parameters in different sleep stages are investigated. The four subjects each underwent five sessions in which different stimulus parameters were varied. The results are summarised as follows:-

(i) As the subject progresses from the awake state (S0) through the classification to deep sleep, both the first and second harmonic amplitudes decrease.

This result is shown in Fig. 4.1. The amplitude of the first

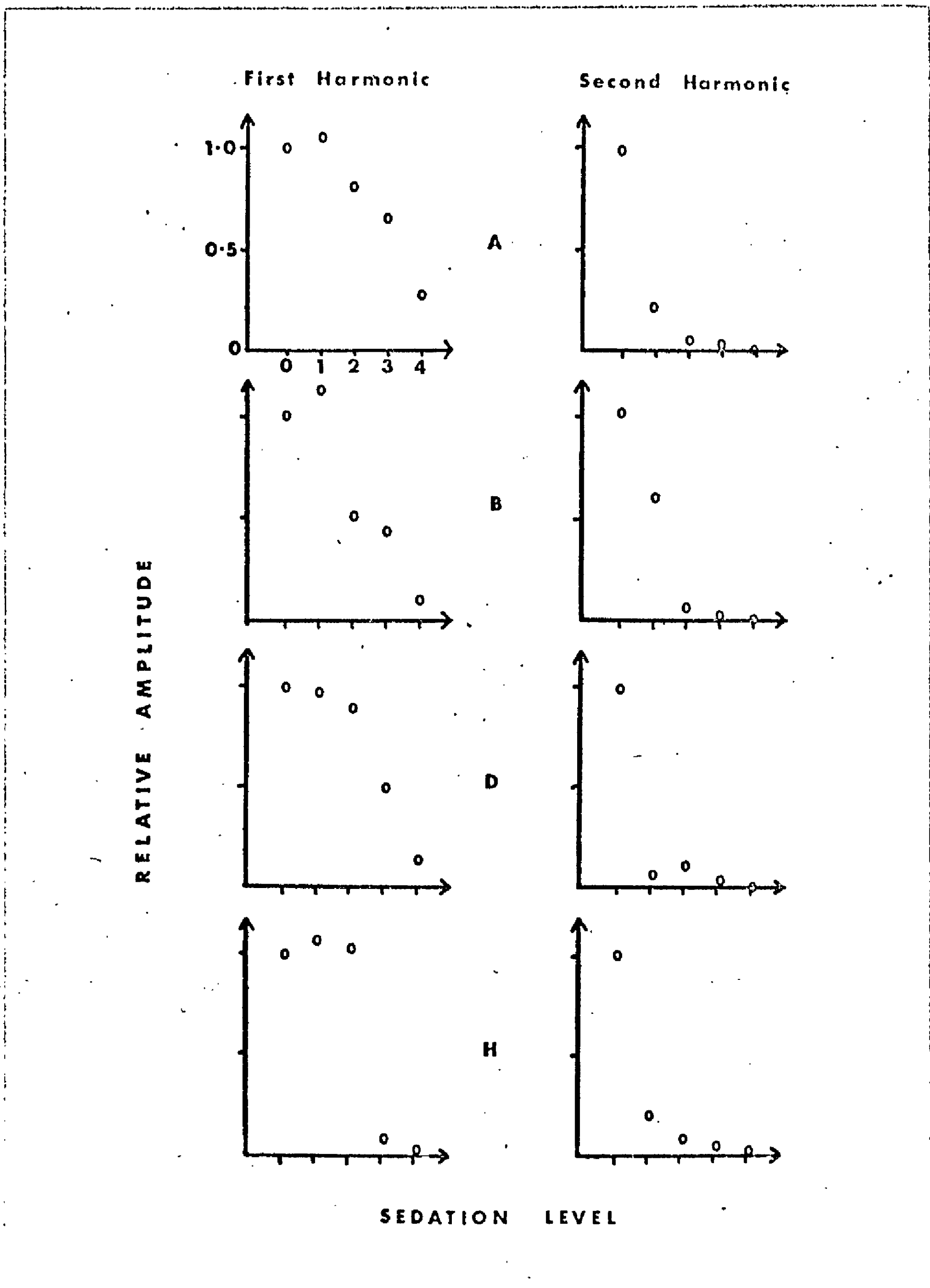


Figure 4.1 Variation of the amplitude of the corrected first and second harmonics with sleep stage, for Subjects A, B, D and H.

harmonic increases slightly in stage 1 and then decreases progressively as the higher stages of sleep are approached. The second harmonic amplitude falls rapidly, even in the states of drowsiness and light sleep, indicating that a large degree of the non-linearity in the system is removed. The results from the four subjects are very similar, and are therefore collected and the resultant relationship between harmonic amplitude and sleep stage is displayed in Fig. 4.2.

The results obtained are encouraging from the point of view of audiometric assessment. The optimal test situation for electrophysiological purposes is stage 1 or 2, which is just the situation for drowsiness and light sleep we require to remove the clinical difficulties in hyperactive children.

Further results quoted compare the effect of stimulus parameters for the four subjects in sleep stage 2, with the results from the awake state reported in Chapter 3.

(ii) The response characteristics as a function of the modulation frequency, and parameters of the corrected first harmonic amplitude are shown in Table 4.I. In this experiment the relative amplitude of the second harmonic is negligible. These results may be seen to be very similar to those obtained in the awake state (Table 3.I). The phase characteristics are identical to those described in Chapter 3.

(iii) As the modulation depth is varied between zero and 100%, the amplitude of the first harmonic saturates at around 60% modulation depth as in the awake state.

(iv) The behaviour as the carrier frequency is varied is also identical to that in the awake state.

(v) The parameters of the growth and decay of the response are more likely to vary with subject state. The experimental results for the previously defined parameters, PS, PF and P50 are shown in Table 4.II. The data exhibit less consistency than those for the awake state, but are in a similar range. The decay process appears to be

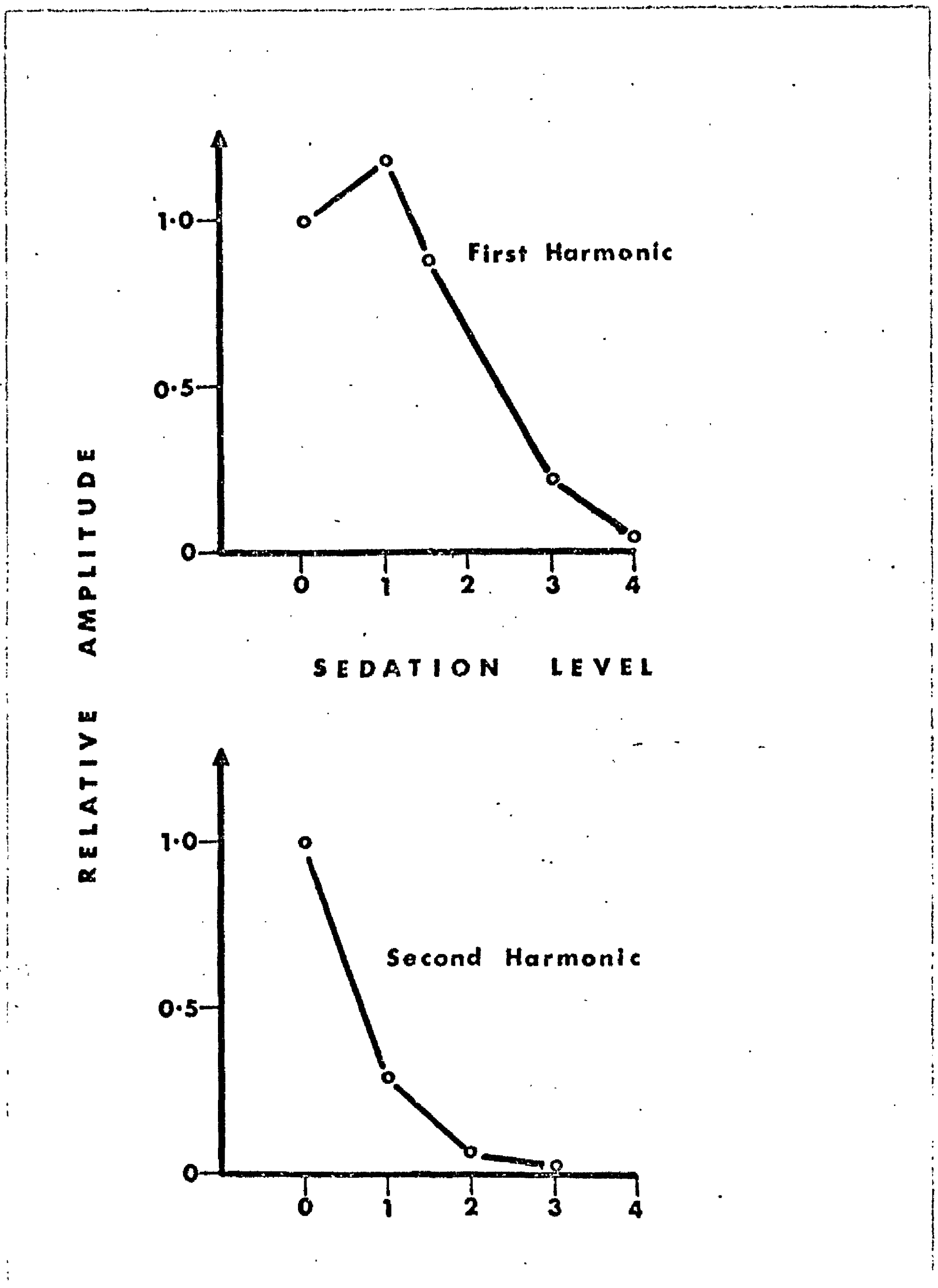


Figure 4.2 Grouped data for the first and second corrected harmonic amplitude as a function of sleep stage.

	SUBJECT			
	A	B	D	H
Number of Peaks	1	1	2	1
Centre Frequency Hz	10.0	9.0	7.0	8.0
Amplitude μV	2.3	1.1	2.1	2.1
F.W.H.M. Hz.	2.1	1.6	3.0	1.2
Centre Frequency Hz	-	-	14.5	-
Amplitude μV	-	-	0.4	-
F.W.H.M. Hz.	-	-	2.1	-

TABLE 4.I

Parameters of the corrected first harmonic amplitude in sleep stage 2.

Subject	PS	PF	P50
A	600	1300	1700
B	400	1700	2400
D	400	1300	1900
H	500	1400	2100

TABLE 4.II

Parameters of response growth and decay of the first harmonic in sleep stage 2.

accelerated, with a lower value for the parameter P50.

(vi) The presence or absence of a response component is ascertained, as in other experiments where the stimulus intensity is varied, by statistically comparing the amplitude of the normal average first harmonic with that of the plus-minus average, using a Student's t-test. The resultant t-coefficients are shown in Table 4.III. The maximum intensity used is 50 dB HTL to avoid waking the subject. The results again compare well with those obtained in the awake state.

4.3 Monaural and Binaural Stimulation

The results in this and preceding chapters have all been obtained using binaural stimulation on normal hearing subjects. This section investigates the effect of monaural and binaural stimulation on one normal hearing subject and one subject with a unilateral hearing loss. The normal subject is Subject A from the principal group introduced in Chapter 2, and the hearing impaired subject is labelled J. Subject J has a 45 dB perceptive hearing loss at 1000 Hz in the right ear.

The two subjects each participated in four experimental sessions and the parameters of the responses are investigated for the different modes of stimulation. The results are summarised below:

(i) The amplitude characteristics of the response, as the modulation frequency is varied between 5 Hz and 15 Hz, are shown in Table 4.IV for the corrected first harmonic. The experiments were performed with a carrier frequency of 1000 Hz, a modulation depth of 60% and a stimulus intensity of 50 dB above the threshold of stimulation. For Subject J, appropriate masking was used during right ear stimulation, where the stimulus intensity was 95 dB HTL. The parameters for binaural stimulation of Subject A are of course available from the experiments described in Chapter 2. The results in Table 4.IV clearly indicate that the amplitude characteristic as a function of modulation frequency is

Intensity dB HTL	t-value
50	5.14*
40	3.91*
30	3.04*
20	2.62*
10	1.90
0	0.22

TABLE 4.III

Statistical comparison of normal and plus-minus averages as a function of stimulus intensity in sleep stage 2.

* Denotes a significant difference at the 95% level.

Subject	Centre Frequency Hz	Amplitude μV	F.W.H.M. Hz
A (Binaural)	10.5	2.5	2.0
A (Left ear)	10.5	2.3	2.0
A (Right ear)	11.0	2.6	2.2
J (Binaural)	12.5	3.2	2.6
J (Left ear)	12.0	3.6	2.4
J (Right ear)	12.5	3.3	2.4

TABLE 4.IV

Parameters of the corrected first harmonic for monaural and binaural stimulation for Subject A (normal hearing) and Subject J (45 dB right perceptive loss at 1000 Hz).

independent of the mode of stimulation for both the normal hearing and the hearing impaired subject. The phase characteristics are identical to those described in Chapter 3.

(ii) For both monaural and binaural stimulation the amplitude of the corrected first harmonic saturates at around 60% modulation depth, as this is varied between zero and 100%.

(iii) The parameters PS, PF and P50, for the growth and decay of the response are shown in Table 4.V. Again the behaviour is found not to vary with the mode of stimulation.

There is found to be no difference in the response behaviour whether the stimulation is delivered monaurally or binaurally for the normal hearing subject or the subject with unilateral hearing loss. The above experiments were performed at equal intensity (50 dB) above threshold (that is 50 dB and 95 dB for Subject J) and the effect of hearing loss on the response amplitude is investigated in the sections dealing with threshold determination.

4.4 Determination of Optimal Modulation Frequency

The modulation frequency which elicits the maximum response amplitude exhibits a large inter-subject variability, as has been clearly demonstrated in Chapter 3. In fact, this inter-subject variability is one of the main limitations in applying the responses from amplitude modulated stimulation to audiometric assessment. The first step when a subject presents for assessment is to determine the optimal frequency of modulation for that subject.

This is achieved by arranging for the modulation signal generator to scan automatically in steps between modulation frequencies of 5 Hz and 15 Hz in steps of 1 Hz.

This is possible using the voltage controlled oscillator facility available on the Hewlet-Packard function generator. The timing is arranged so that 1000 cycles of each modulation frequency are presented

Subject	PS	PF	P50
A (Binaural)	500	1400	2200
A (Left ear)	500	1500	2500
A (Right ear)	400	1400	2300
J (Binaural)	400	1300	1800
J (Left ear)	300	1400	2100
J (Right ear)	400	1200	2100

TABLE 4.V

Parameters of response growth and decay of the corrected first harmonic for monaural and binaural stimulation for Subject A (normal hearing) and Subject J (45 dB right perceptive loss at 1000 Hz).

to the subject. The equivalent stimulus presentation times are shown in Table 4.VI and the total time to scan between 5 Hz and 15 Hz is 20 minutes 35 seconds. The analysis described previously is performed, and the response parameters examined to determine the optimal frequency of modulation. The efficiency of the above procedure is investigated on three subjects: Subject K (30 dB right perceptive loss at 1000 Hz), Subject L (70 dB left perceptive loss at 1000 Hz) and Subject M (65 dB bilateral perceptive loss at 1000 Hz). Experiments are performed at a modulation depth of 60%, a carrier frequency of 1000 Hz, and under conditions of monaural and binaural stimulation. The first 500 samples at each modulation frequency are ignored, and the second 500 samples used to compile the single cycle averages. Each subject participated in one experimental session and the stimulus intensity presented to each subject is appropriate to the behavioural threshold, as dissussed below in a summary of the results.

(i) The amplitude of the corrected first harmonic as a function of modulation frequency is shown in Table 4.VII for Subject K. A stimulus intensity of 60 dB HTL is used for left ear stimulation, 90 dB HTL for right ear stimulation, and 60 dB HTL for binaural stimulation. During right ear stimulation, appropriate masking is presented to the left ear. Inspection of Table 4.VII shows that the amplitude is maximal at a modulation frequency of 8 Hz for all three modes of stimulation. The previous section demonstrated that the mode of stimulation did not affect response parameters, and so these results indicate the ability of the procedure to determine the optimal modulation frequency in an ear with a 30 dB loss.

(ii) Table 4.VIII shows the results for Subject L for the different modulation frequencies. A stimulus intensity of 100 dB HTL is used for left ear stimulation (with appropriate masking to the right ear) and 60 dB HTL for right ear and binaural stimulation. The maximum first harmonic amplitude is found at a modulation frequency of 12 Hz for all

Modulation Frequency Hz	Time for 1000 cycles of Modulation secs.
5	200
6	167
7	143
8	125
9	111
10	100
11	91
12	83
13	77
14	71
15	67

Total time = 20 mins. 35 secs.

TABLE 4.VI

Modulation frequency determination times.

Modulation Frequency Hz	Amplitude of Corrected First Harmonic		
	Left Ear	Right Ear	Binaural
5	0.8	0.4	1.0
6	1.4	1.0	1.3
7	1.9	1.2	2.1
8	2.6	1.9	2.9
9	2.4	1.6	2.0
10	2.1	1.4	2.1
11	1.6	0.9	1.4
12	0.6	0.7	0.9
13	0.3	0.7	0.5
14	0.2	0.4	0.1
15	0.2	0.1	0.2

TABLE 4.VII

Determination of optimal modulation frequency for Subject K (30 dB right perceptive loss at 1000 Hz).

Modulation Frequency Hz	Amplitude of Corrected First Harmonic		
	Left Ear	Right Ear	Binaural
5	0.2	0.4	0.7
6	0.4	1.1	1.2
7	0.2	0.2	0.6
8	0.3	0.7	0.6
9	0.4	1.2	1.1
10	0.4	1.2	1.4
11	0.7	2.0	2.1
12	1.1	2.6	2.9
13	0.6	2.1	2.3
14	0.3	1.2	1.6
15	0.1	0.4	0.9

TABLE 4.VIII

Determination of optimal modulation frequency for Subject L (70 dB left perceptive loss at 1000 Hz).

modes of stimulation, indicating the ability of the procedure to determine optimal modulation frequency in an ear with a loss of 70 dB.

(iii) Table 4.IX shows the results for Subject M. A stimulus intensity of 100 dB HTL is used for all modes of stimulation. The maximum amplitude of the first harmonic is achieved at a modulation frequency of 10 Hz for left ear, right ear and binaural stimulation. As this subject has bilateral hearing loss, no comparison with stimulation of a normal ear may be performed. However, the consistency of the results between the three modes of stimulation indicates the reliability of the procedure.

These results indicate that the procedure of scanning through the range of modulation frequencies in a series of steps may be used to determine the optimal modulation frequency in both normal ears and in ears with a varying degree of hearing loss.

4.5 Threshold Determination in Adults

A group of ten adult subjects with a variety of hearing loss in either ear is investigated to determine the ability of steady state responses to amplitude modulated stimulation, to predict behavioural threshold. At the time of assessment, all information regarding the hearing level of each subject was rigorously withheld from the investigator.

The first step in the investigation is to determine the optimal frequency of modulation for each subject. This is achieved by the procedure described in the preceding section, using a modulation depth of 60%, a carrier frequency of 1000 Hz and binaural stimulation. The stimulus intensity is adjusted to be comfortably loud for each individual. The results are analysed as described previously, and the frequency of modulation at which the corrected first harmonic amplitude is maximal, is determined. The optimal modulation frequencies for the ten subjects are given in Table 4.X. The large inter-subject variability found in

Modulation Frequency Hz	Amplitude of Corrected First Harmonic		
	Left Ear	Right Ear	Binaural
5	0.2	0.1	0.2
6	0.3	0.3	0.3
7	0.2	0.3	0.3
8	0.4	0.4	0.5
9	0.9	1.0	0.9
10	1.2	1.2	1.3
11	0.8	0.7	0.8
12	0.3	0.5	0.4
13	0.5	0.2	0.2
14	0.2	0.1	0.3
15	0.2	0.3	0.2

TABLE 4.IX

Determination of optimal modulation frequency for Subject M (65 dB bilateral perceptive loss at 1000 Hz).

Subject	Optimal Frequency of Modulation Hz
A1	8
A2	13
A3	9
A4	9
A5	11
A6	14
A7	12
A8	8
A9	9
A10	11

TABLE 4.X

Optimal modulation frequencies for the 10 adult clinical subjects.

Chapter 3 is again clearly demonstrated.

Experiments are now performed for each ear separately, with appropriate masking to the contralateral ear, in which the stimulus intensity is progressively decreased, and the level at which the normal average (response plus residual EEG) is no longer significantly greater than the plus-minus average (residual EEG only) is taken as the "steady-state threshold". The resultant thresholds for each ear are shown in Table XI for the ten subjects.

The accuracy of these steady-state thresholds is assessed by comparison with thresholds obtained from averaged EEG audiometry to tone-burst stimulation and the behavioural thresholds. In averaged EEG audiometry to transient stimulation (see Chapter 1) an observer value-judgement is made to determine the presence or absence of the response waveform. The resultant "transient response thresholds" are shown in Table 4.XII, and comparison with Table 4.XI indicates the consistency between the steady-state thresholds and the transient response thresholds. The steady-state thresholds appear to be slightly less sensitive. The similarity between the two thresholds is encouraging as the reliability of the transient response thresholds in adults is high (Chapter 1).

The behavioural thresholds obtained by conventional audiometry are shown in Table 4.XIII. Comparison between the steady state thresholds (Table 4.XI) and these behavioural thresholds show that the steady state method consistently overestimates the hearing loss by an average of between 15 dB and 20 dB. A linear correlation performed between the thresholds yields a correlection coefficient of 0.988, and a linear regression analysis yields the relationship

$$B = 0.958\ S - 15.5$$

where B is the behavioural threshold and S is the steady state threshold in dB HTL.

Subject	Steady State Threshold dB HTL	
	Left Ear	Right Ear
A1	30	70
A2	50	60
A3	110	40
A4	30	60
A5	80	90
A6	40	110
A7	70	40
A8	20	90
A9	40	80
A10	60	110

TABLE 4.XI

Steady state thresholds at 1000 Hz to amplitude modulated stimulation for the 10 adult clinical subjects.

Subject	Transient Response Threshold dB HTL	
	Left Ear	Right Ear
A1	20	60
A2	50	50
A3	90	30
A4	20	60
A5	80	90
A6	30	110
A7	70	30
A8	20	80
A9	30	70
A10	50	90

TABLE 4.XII

Transient response thresholds at 1000 Hz for the 10 adult clinical subjects.

Subject	Behavioural Threshold dB HTL	
	Left Ear	Right Ear
A1	15	50
A2	35	40
A3	90	20
A4	10	45
A5	65	75
A6	20	95
A7	60	25
A8	5	70
A9	20	55
A10	40	80

TABLE 4.XIII

Behavioural thresholds at 1000 Hz for the 10 adult clinical subjects.

4.6 Threshold Determination in Children

A procedure similar to the preceding section is performed on a group of ten children presented clinically with suspected hearing loss in either one or both ears. Again the investigator is in ignorance of the result of any previous assessment. The children were aged between 3 years and 7 years at the time of investigation and all were difficult, if not impossible to assess using conventional audiometric techniques. All the children required sedation and all experiments were performed with the subject in sleep stage 2 (see Section 4.2).

The optimal frequency of modulation is determined by the frequency stepping method and the results are shown in Table 4.XIV. Again the large degree of inter-subject variability is evident.

The steady state thresholds are determined in the same way as for adult subjects by successively decreasing the stimulus intensity until the analysis procedure can no longer detect the presence of a response component, and they are shown in Table 4.XV.

As with the adult subjects the transient response thresholds are also determined and these are shown in Table 4.XVI for comparison. The two sets of thresholds may be seen to be broadly similar.

For this group of child subjects it was possible to obtain behavioural thresholds in only six of the subjects, due to the clinical difficulties in dealing with children. Indeed this is the raison d'etre for the existence of electrophysiological audiometric techniques. The behavioural thresholds that were obtainable are shown in Table 4.XVII, and comparison with the steady state thresholds (Table 4.XV) again shows that the steady state thresholds overestimate the hearing loss by about 20 dB.

If linear correlation and regression are performed on the two sets of thresholds, the resultant correlation coefficient is 0.937, and the regression relationship is:-

$$B = 0.918\ S - 15.7$$

where B is the behavioural threshold and S is the steady state threshold.

Subject	Optimal Frequency of Modulation Hz
C1	7
C2	12
C3	11
C4	9
C5	8
C6	11
C7	12
C8	11
C9	9
C10	9

TABLE 4.XIV

Optimal modulation frequencies for the 10 child clinical subjects.

Subject	Steady State Threshold	
	Left Ear	Right Ear
C1	40	80
C2	20	50
C3	80	60
C4	40	60
C5	100	50
C6	30	20
C7	50	60
C8	70	60
C9	80	70
C10	80	60

TABLE 4.XV

Steady state thresholds at 1000 Hz to amplitude modulated stimulation for the 10 child clinical subjects.

Subject	Transient Response Threshold dB HTL	
	Left Ear	Right Ear
C1	30	60
C2	20	40
C3	70	60
C4	50	30
C5	90	40
C6	20	20
C7	40	30
C8	70	60
C9	90	50
C10	80	70

TABLE 4.XVI

Transient response thresholds at 1000 Hz for the 10 child clinical subjects.

Subject	Behavioural Threshold dB HTL	
	Left Ear	Right Ear
C1	20	55
C2	10	25
C3	-	-
C4	20	30
C5	-	-
C6	-	-
C7	35	40
C8	-	-
C9	70	50
C10	60	30

TABLE 4.XVII

Behavioural thresholds at 1000 Hz for the 10 child clinical subjects.

4.7 Summary

The effect of sedation, to make the subject behaviour clinically acceptable, on the steady state potentials elicited by amplitude modulated stimulation has been investigated. Good responses are obtained in sleep stages 1 and 2, while deeper sleep states considerably reduce the response amplitude. The form of the response and its function with respect to stimulus parameters (such as modulation frequency) is unaltered by the use of sedation. This is a considerable advantage over the averaged EEG responses to transient (tone burst) stimulation, where sedation may change the form of the response waveform.

Experiments performed using monaural and binaural stimulation indicate no differences in the response as a function of stimulus parameters. Thus the optimal stimulus conditions for a normal ear may be used to determine threshold in a hearing impaired ear.

One of the outstanding problems in the application of these responses to amplitude modulated stimulation is the large inter-subject variation in the response amplitude as a function of modulation frequency. Thus the optimal modulation frequency requires determination for each subject. A frequency scanning procedure has been developed whereby the modulation frequency is automatically stepped between 5 Hz and 15 Hz and the point where the response maximum occurs is determined. This procedure is found to be effective but the time taken of over twenty minutes is considerable.

Groups of hearing impaired adults and children, for whom the behavioural threshold was unknown at the time of investigation, were investigated and the analysis used to determine the electrophysiological threshold of the steady state potentials. The analysis into harmonic components is found to provide steady state thresholds comparable to the electrophysiological thresholds to transient stimulation, whilst removing the requirement of an observer value judgement. Comparison with the behavioural thresholds, where they are available demonstrates the excellent consistency of the responses with correlation coefficients of 0.988 for the adults and 0.937 for the children. The steady state thresholds consistently overestimate the degree of hearing loss by about 20 dB.

CHAPTER 5

Steady State Potentials and Frequency Modulation Stimulus Parameters

5.1 Introduction

The presence within the auditory pathway of neurones which are sensitive to a change in frequency as opposed to intensity is well established (49), and the application of averaged EEG responses to a frequency change is receiving widespread attention (37, 38) with a view to improving the reliability of averaged EEG audiometry. This chapter describes experiments using frequency modulated stimulation, to determine the optimal stimulus parameters for audiological application. These experiments are similar to those described in Chapter 3 for amplitude modulated stimulation. The same eight normal hearing subjects (six adults and two children) form the principal subject group and five children (three of whom participated in the amplitude modulation experiments) form a subsidiary group to investigate any differences between adults and children. As in Chapter 3, all the experiments are performed with the subjects sitting quietly and reading material of their own choice.

5.2 Preliminary Results

Preliminary experiments indicate that responses are obtainable in the range 9 Hz to 13 Hz at a modulation depth of 8%. For all subjects the first and second harmonics predominate, and therefore the bandwidth of the EEG signal is restricted between 3.2 Hz and 32 Hz. In view of the results obtained for amplitude modulation, the averages are compiled from 1000 samples, while the initial 500 samples presented to the subject are ignored to allow the response to stabilise.

A detailed series of experiments is now performed to investigate the effect of stimulus parameters in which:-

(a) The modulation frequency is varied between 5 Hz and 15 Hz.

(b) The modulation depth is varied between zero and 10%.

(c) The carrier frequency is varied between 500 Hz and 4000 Hz.

(d) The growth and decay of the response is investigated.

(e) The stimulus intensity is varied between 80 dB and HTL threshold.

5.3 Effect of Modulation Frequency

The modulation frequency is varied between 5 Hz and 15 Hz in steps of 1 Hz, and the effect on the response parameters investigated. During this series the modulation depth is set at 8%, the carrier frequency at 1000 Hz, the stimulus intensity (which is held constant as described in Chapter 2) at 70 dB HTL, and 1500 cycles of modulation are presented to the subject of which the final 1000 are used to compile the average. Each of the eight principal subjects participated in five experimental sessions and the means of the corrected first harmonic amplitude for each subject are shown in Fig. 5.1. For each of the subjects the response is maximal at around 11 Hz and falls gradually at lower and higher frequencies reaching about 50% of the maximum at 5 Hz and 15 Hz. The details of the response parameters are given in Table 5.I for the amplitude of the first harmonic; showing the modulation frequency where the response is a maximum, and the amplitude of that response. Inspection of Fig. 5.1 indicates little of the inter-subject variability observed for amplitude modulated stimulation, and the only large variation between subjects is the absolute value of the response amplitude. This varies from 0.9 μV to 1.9 μV, but the form of the variation with modulation frequency is similar for all subjects. The results from the eight subjects may then be grouped and Fig. 5.2 shows the variation with modulation frequency of the corrected first and second harmonics for the collected data. The results are expressed in terms of relative amplitude (with the maximum achieved for each subject set at 1.0 as in Fig. 5.1) to remove the differences in absolute amplitude. It may be seen that a modulation frequency of 11 Hz elicits adequate responses for all subjects.

Subject	Centre Frequency Hz	Amplitude μV
A	11.0	1.1
B	12.5	0.9
C	11.0	1.8
D	11.0	1.2
E	11.0	1.9
F	12.0	1.0
G	10.0	1.4
H	11.5	1.7

TABLE 5.I

Parameters of the corrected first harmonic for the eight principal subjects.

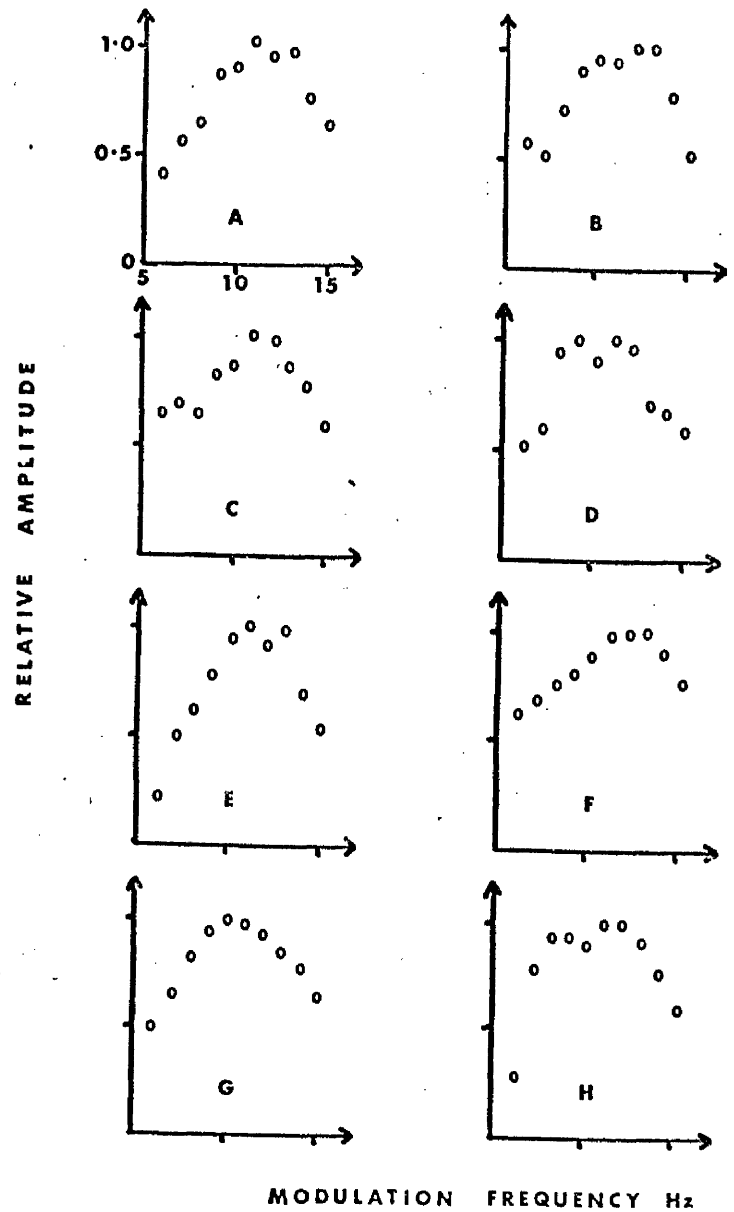


Figure 5.1 Variation of the amplitude of the corrected first harmonic with modulation frequency for the principal subjects.

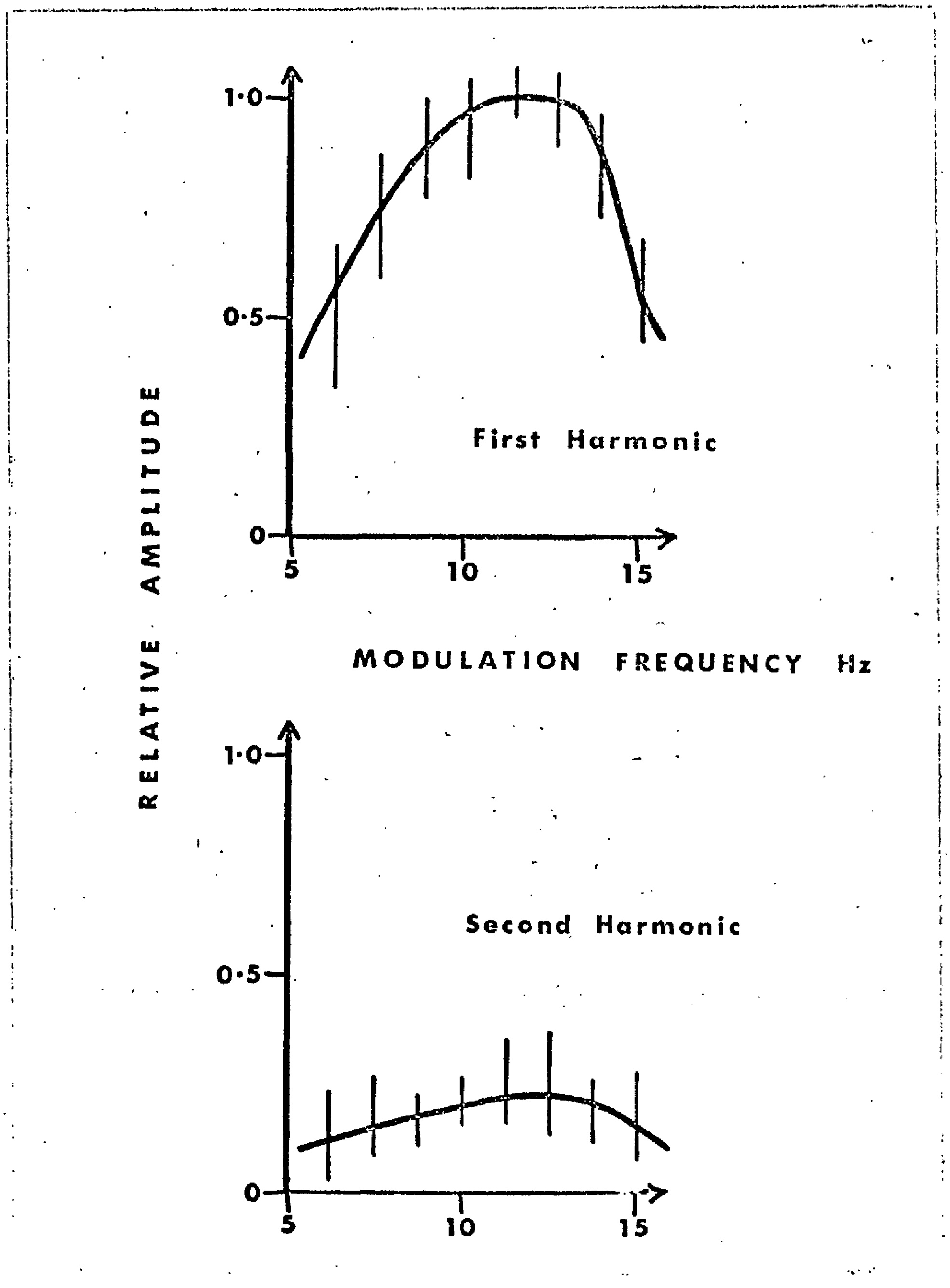


Figure 5.2 Grouped data for the amplitude of the corrected first and second harmonics as a function of modulation frequency.

The amplitude of the second harmonic is relatively stable as a proportion of the first harmonic. Details of the second harmonic parameters are shown in Table 5.II. The variation of the second harmonic amplitude with modulation frequency is small, but the centre frequency for the second harmonic still compares well with that for the first harmonic. Table 5.II also shows the second harmonic as a proportion of the first taken at the centre frequency of the first harmonic, and the relative stability is clear.

For all the subjects, the phase of both the first and second harmonic exhibits a broadly linear variation with modulation frequency.

A linear correlation is performed between the first harmonic amplitudes of the normal and plus-minus averages as a function of modulation frequency (as for the amplitude modulated stimulation) and the resultant correlation coefficients are shown in Table 5.III. As in Chapter 3, there exists no significant correlation between the response plus residual EEG (normal average) and the residual EEG (plus-minus average), which indicates that the response is independent of the subject's EEG characteristics.
This point is pursued further in Chapter 7.

5.4 Effect of Modulation Depth

The modulation depth is defined in Fig. 5.3, which is a diagrammatic representation of a Sonograph output, used to monitor the frequency modulated stimulus as described in Chapter 2. As in the case of amplitude modulated stimulation, a modulation depth of zero represents a pure tone of constant intensity, and no response would be expected. This has already been verified in Chapter 3.

The modulation depth is varied from zero to 10% for each of the eight principal subjects on four separate occasions. The modulation frequency is set at 11 Hz for all subjects, the carrier frequency at 1000 Hz, the stimulus intensity at 70 dB, and as before the final 1000 tokens of the 1500 cycles of modulation are used to compile the average. The analysis procedure is

Subject	Centre Frequency Hz	$\frac{F_2}{F_1} \times 100\%$
A	12.0	12
B	12.0	19
C	12.5	9
D	11.0	16
E	11.5	14
F	12.5	20
G	11.0	11
H	12.0	14

TABLE 5.II

Parameters of the corrected second harmonic for the eight principal subjects.

Subject	Correlation Coefficient
A	0.19
B	0.06
C	0.14
D	0.13
E	0.21
F	0.07
G	0.10
H	0.09

TABLE 5.III

Linear correlation between the first harmonic amplitudes of the normal and plus-minus averages.

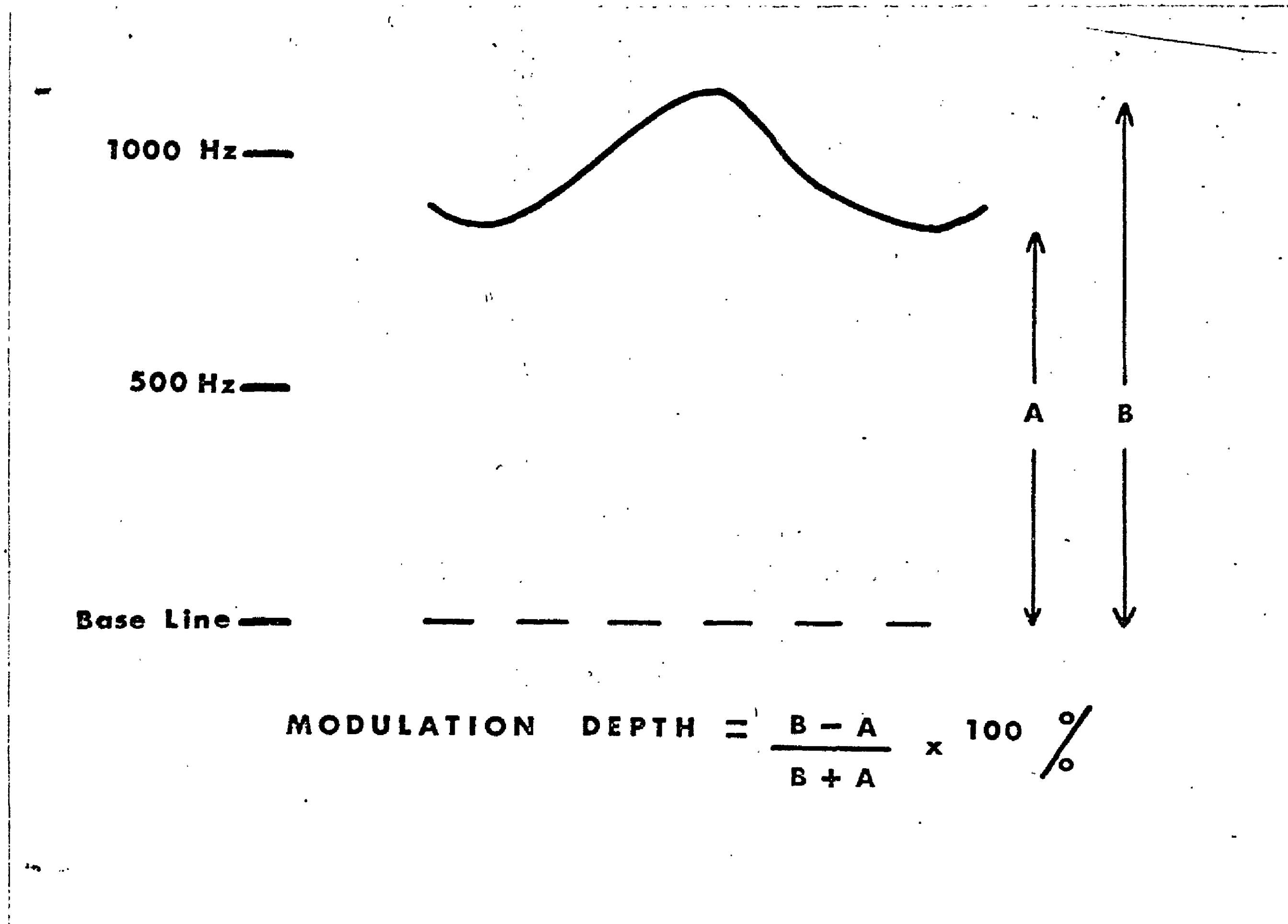


Figure 5.3 Definition of Modulation Depth.

identical to that for amplitude modulation, as the frequency modulated stimulation produces a signal which is a change in amplitude.

Fig. 5.4 shows the means of the corrected first harmonic for each subject. The phase of the first and second harmonics (the only harmonics present to any degree for all subjects) are found to be invariant with modulation depth. The results in Fig. 5.4 have been plotted in terms of the percentage of the maximum value achieved for each subject to account for the differences in absolute amplitude of the responses, and therefore enable inter-subject comparison. The eight subjects exhibit a similar variation in the amplitude of the first harmonic with changes in modulation depth. The data are therefore collected and the results are shown in Fig. 5.5 for the corrected first and second harmonics. The first harmonic amplitude increases as the modulation depth is increased from zero, until after a modulation depth of around 4→5% a plateau is reached. The second harmonic amplitude increases monotonically. A modulation depth of 5% is suitable for all subjects to minimise harmonic distortion.

5.5 Effect of Carrier Frequency

To investigate whether the steady state responses are reliably obtainable throughout the auditory range, experiments were performed at carrier frequencies of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.

For all subjects the optimal parameters from the two preceding sections were used, with a modulation frequency of 11 Hz and a modulation depth of 5%. Thus at a carrier frequency of 500 Hz the maximum frequency excursion is 10 Hz, and extends to an excursion of 200 Hz at a carrier frequency of 4000 Hz. The intensity level (which for this mode of stimulation is deliberately held constant) is set at 70 dB HTL, and, by extrapolation from the results to amplitude modulated stimulation, 1500 cycles of modulation are presented of which the final 1000 are used to compile the average. Thus at a modulation frequency of 11 Hz, each determination takes a time of 137 seconds. Each subject participated in

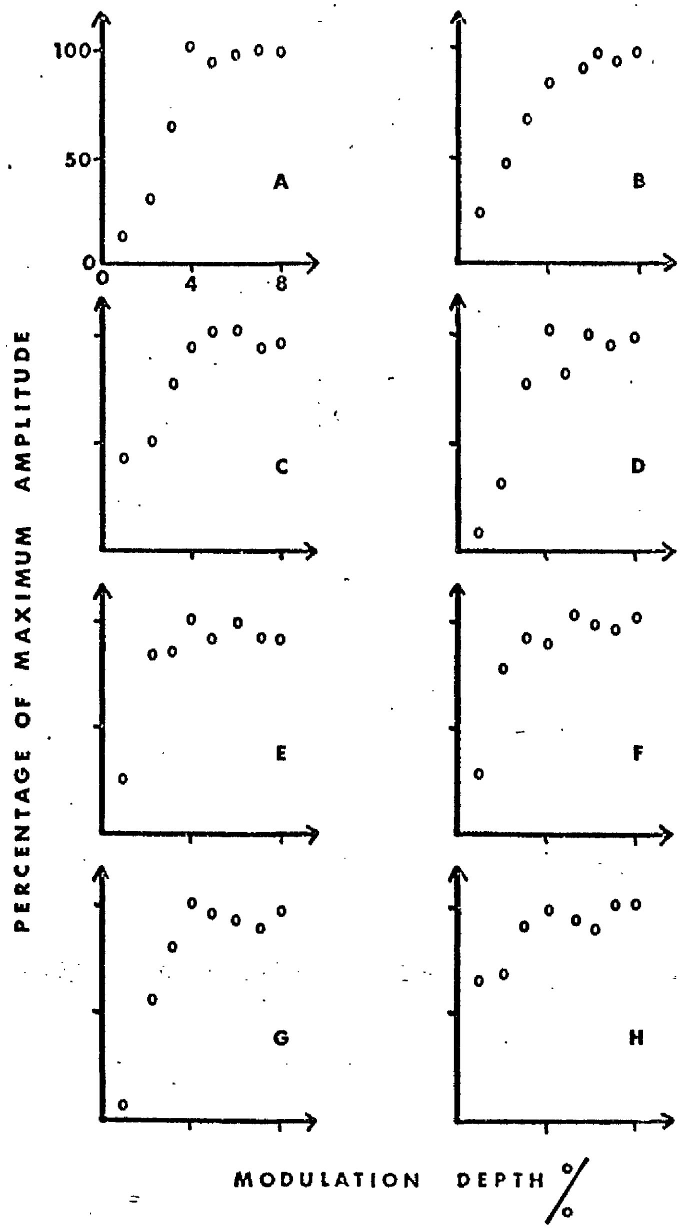


Figure 5.4 Variation with modulation depth of the amplitude of the corrected first harmonic for the principal subjects.

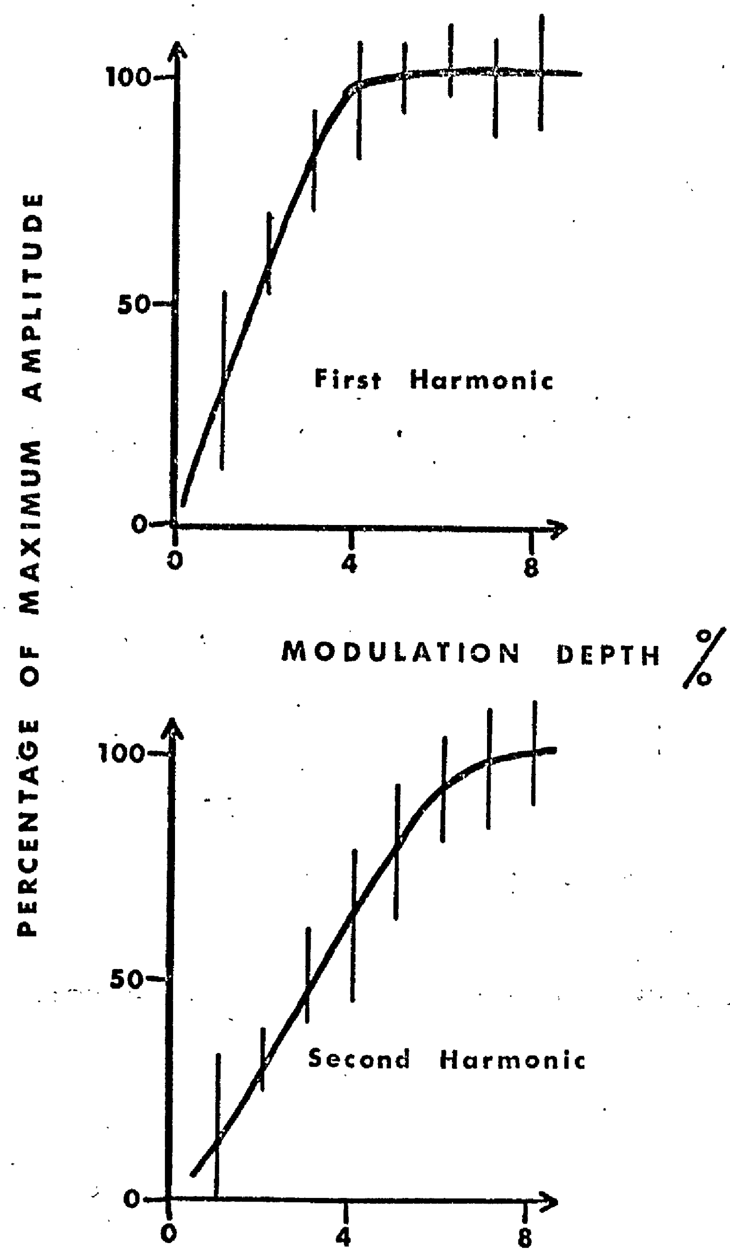


Figure 5.5 Grouped data for the amplitude of the corrected first and second harmonics as a function of modulation depth.

at least three experimental sessions.

Fig. 5.6 shows the variation with carrier frequency of the amplitude of the corrected first harmonic for the eight principal subjects. There is very little difference in the response behaviour for the different subjects. The maximum responses are achieved at the lower frequencies, and the amplitude falls to around 50% of the maximum as the carrier frequency is increased to 4000 Hz. A similar variation with carrier frequency is found for the amplitude of the corrected second harmonic, while the phase of all the harmonics present does not change with carrier frequency.

The results have again been presented in the form of percentage of the maximum amplitude achieved to enable inter-subject comparison, and when the data for the eight subjects are collected the variations for the first and second harmonic amplitudes shown in Fig. 5.7 are found.

5.6 Effect of Number of Samples in the Average

The effect on the response of the number of samples used to compile the average depends on the growth and decay parameters of the response, and as mentioned in Chapter 3, will depend greatly on the subjective state of the subject. The effects of sedation for clinical purposes on the response are described in Chapter 6, and in this section the subject remains physically quite but mentally alert by reading from material of his or her own choice.

The experiments performed are very similar to those described in Chapter 3.6. Recordings are made from each of the eleven subjects using the optimal stimulus parameters determined in the preceding sections. The modulation frequency is 11 Hz, the modulation depth 5%, the carrier frequency 1000 Hz, and the stimulus intensity is 70 dB HTL. The stimulus is presented to the subject for 460 seconds (that is 5000 cycles of modulation at a modulation frequency of 11 Hz), and as in Chapter 3, the response is analysed in sections of 100 cycles of modulation (i.e. 9 seconds).

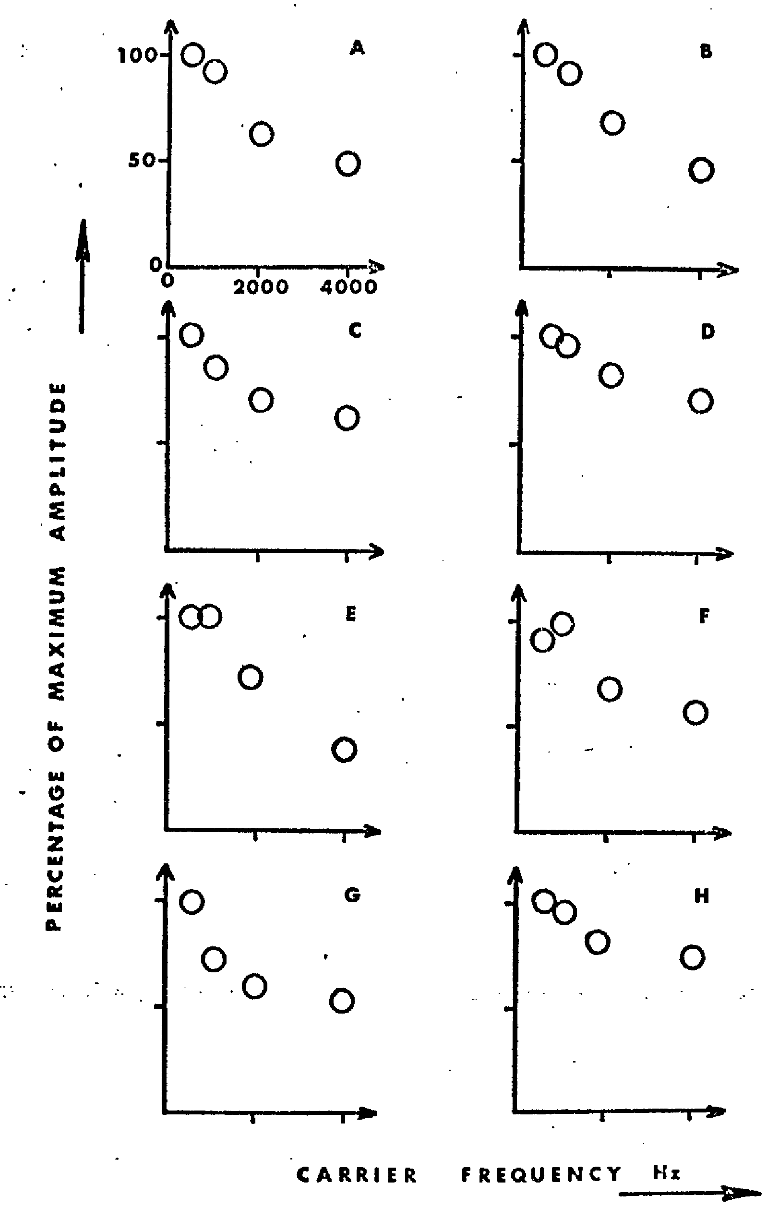


Figure 5.6 Variation of the amplitude of the corrected first harmonic with carrier frequency for the principal subjects.

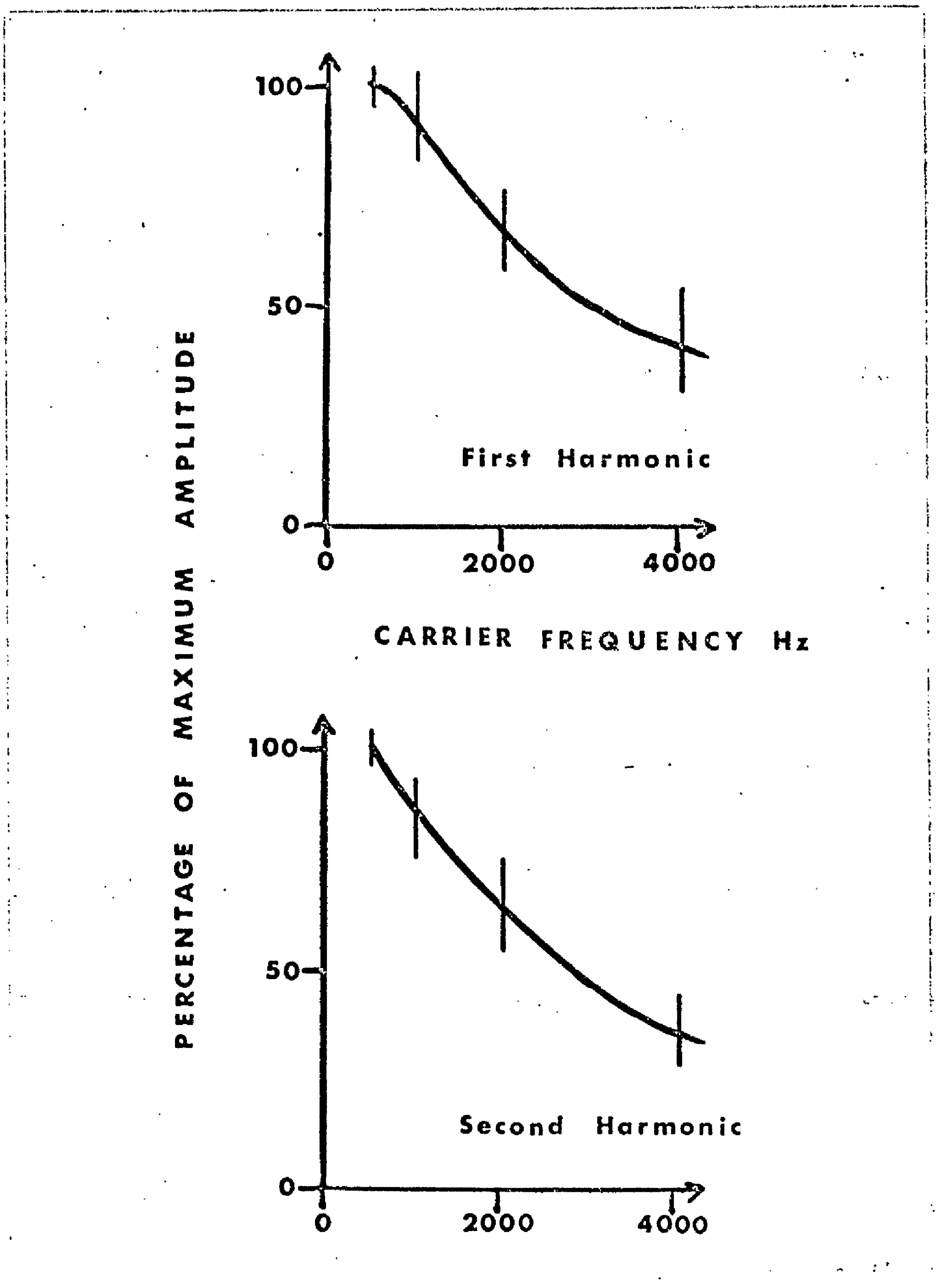


Figure 5.7 Grouped data for the amplitude of the corrected first and second harmonics as a function of carrier frequency.

The amplitude of the corrected first harmonic is then calculated as before.

The growth and decay of the response, as a function of cycles of modulation presented, is shown in Fig. 5.8 for Subject A. The amplitude exhibits an early rapid increase, reaches a plateau and then decreases gradually as the stimulus is continuously applied. The three parameters, PS (number of cycles to the start of plateau), PF (number of cycles to the end of the plateau) and P50 (number of cycles to the point where the response has declined to 50% of the maximum value) are used to characterise the growth and decay of the response for the eight subjects. The values of PS, PF and P50 for the different subjects are shown in Table 5.IV.

Inspection of the results indicates relatively little variation in the parameters between the subjects. As in Chapter 3, a reasonable choice to optimise the response is to ignore the first 500 samples (i.e. the first 46 seconds at 11 Hz) and use the subsequent 1000 samples (the subsequent 91 seconds) to compile the average. This optimum may only apply to the subject state used however, and if sedation is used the parameters require further investigation. This is described in Chapter 6.

5.7 Effect of Stimulus Intensity

The variation of the response parameters as a function of stimulus intensity, leading to the determination of the detection threshold of the potentials is of paramount importance in their application to audiology. A full assessment of threshold determination is included in Chapter 6. This section investigates the response characteristics as a function of stimulus intensity for the eight principal subjects.

Experiments in the preceding sections have shown that a set of optimal stimulus parameters may be applied to all of the subjects. These parameters are shown in Table 5.V and are used hereafter in all experiments employing frequency modulated stimulation.

The stimulus intensity is varied between zero and 80 dB HTL and the

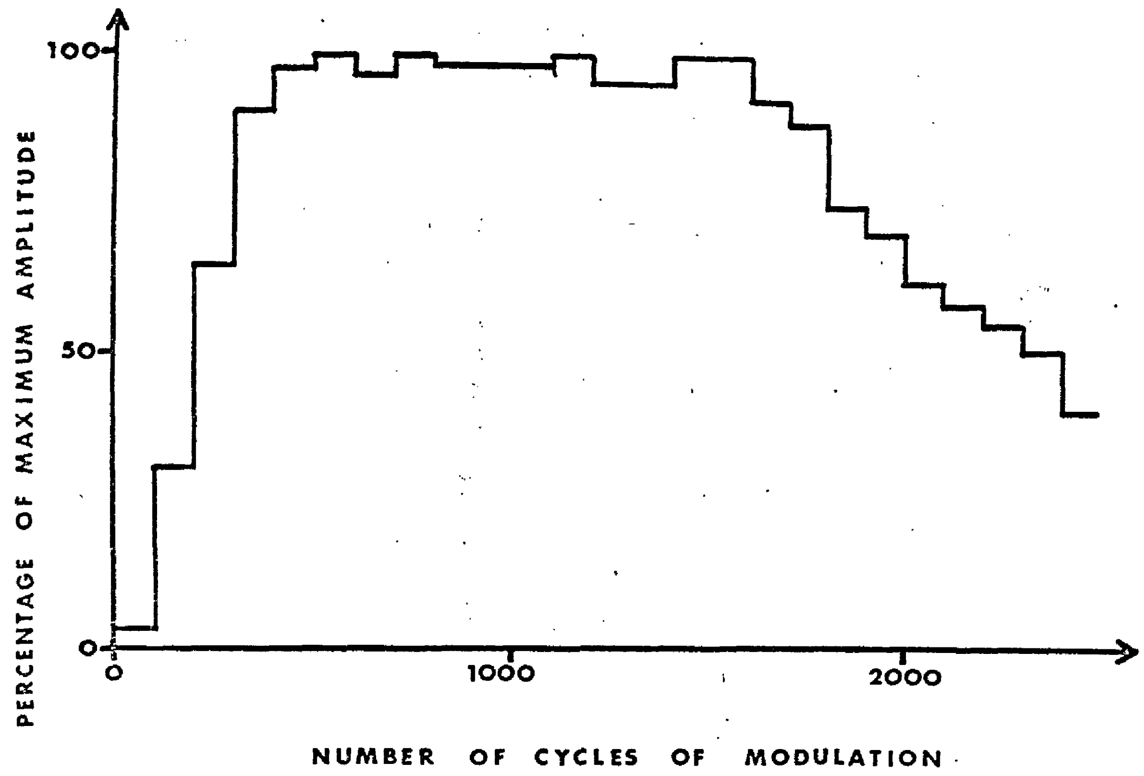


Figure 5.8 Growth and decay of the corrected first harmonic amplitude for Subject A.

Subject	SP	PF	P50
A	500	1500	2300
B	500	1800	2100
C	700	1400	2900
D	600	1900	2400
E	400	1600	2300
F	400	1400	2800
G	600	1500	2700
H	300	1800	2400

TABLE 5.IV

Parameters of response growth and decay for the eight principal subjects.

PS - Number of cycles to start of plateau.

PF - Number of cycles to end of plateau.

P50 - Number of cycles to point where response is 50% of maximum.

Modulation Frequency	= 11 Hz
Modulation Depth	= 5%
Carrier Frequency	= 1000 Hz
Number of Samples in Average	= 1000
Number of samples ignored in response growth period	= 500

TABLE 5.V

Optimal stimulus parameters for frequency modulated stimulation.

responses compiled and analysed in the usual way. The normal and plus-minus averages are compared (that is the presence of a response component is investigated) for each of the eight subjects in three experimental sessions. The means of the first harmonic amplitudes for the two types of averages are shown in Fig. 5.9 as a function of stimulus intensity.

At higher intensity levels a response component is clearly present, while the difference between the two averages decreases as the stimulus intensity is decreased. The eight subjects exhibit a similar pattern of variation, and the results are collected and displayed in Fig. 5.10. The normal average (response plus residual EEG) may be seen to be greater than the plus-minus average (residual EEG alone) until about 40 dB HTL after which the residual EEG activity is predominant.

The first harmonic amplitude of the normal average is compared statistically with the first harmonic amplitude of the plus-minus average using a Student's t-test. The resultant coefficients are shown in Table 5.VI. A significant difference (at the 95% level) is found between the two averages at 40 dB HTL and above. Thus the analysis procedure can detect the presence of a response component at a level 40 dB above threshold.

5.8 Results from Subsidiary Group of Children

The group of eight principal subjects, containing only two children aged six and eleven years, is not representative of the potential clinical population, and so a group of five children aged between two and five years, was investigated. Each member of the subsidiary group attended for one comprehensive experimental session and the results are compared with those from the preceding sections. All experiments were performed at the optimal stimulus parameters given in Table 5.V.

a. Variation with modulation frequency.

As the modulation frequency is varied between 5 Hz and 15 Hz the response parameters are found to vary in a manner comparable to those for

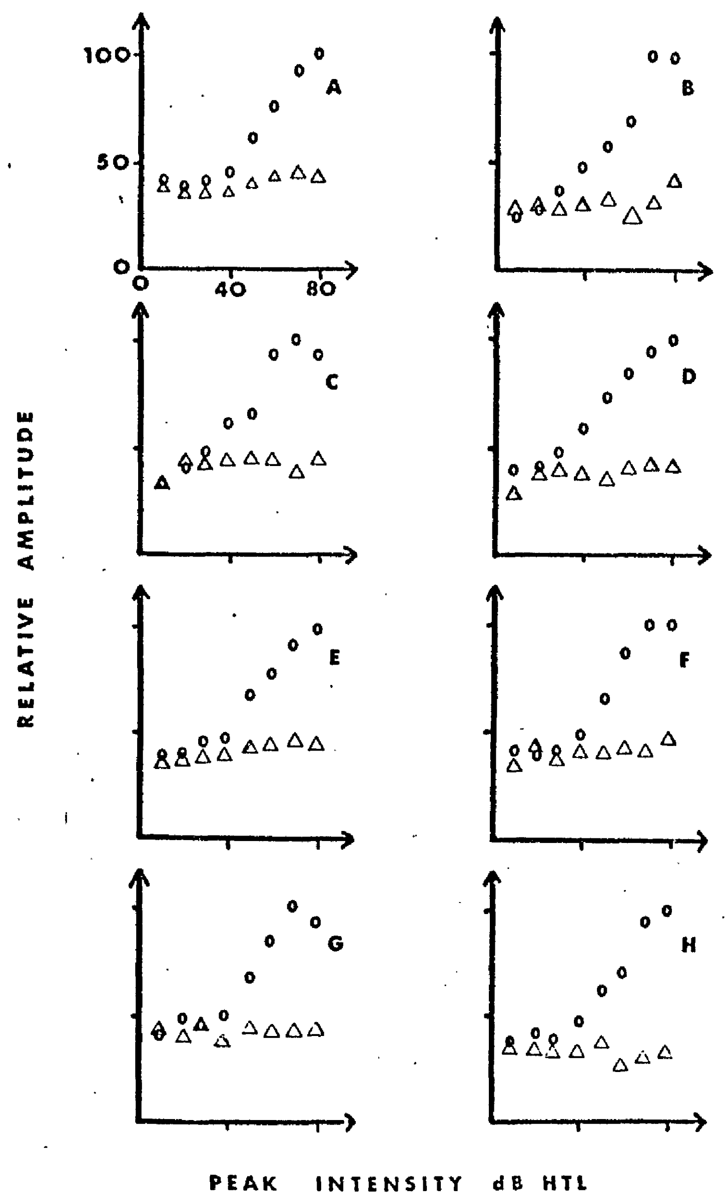


Figure 5.9 Variation with stimulus intensity of the amplitude of the corrected first harmonic for the principal subjects.

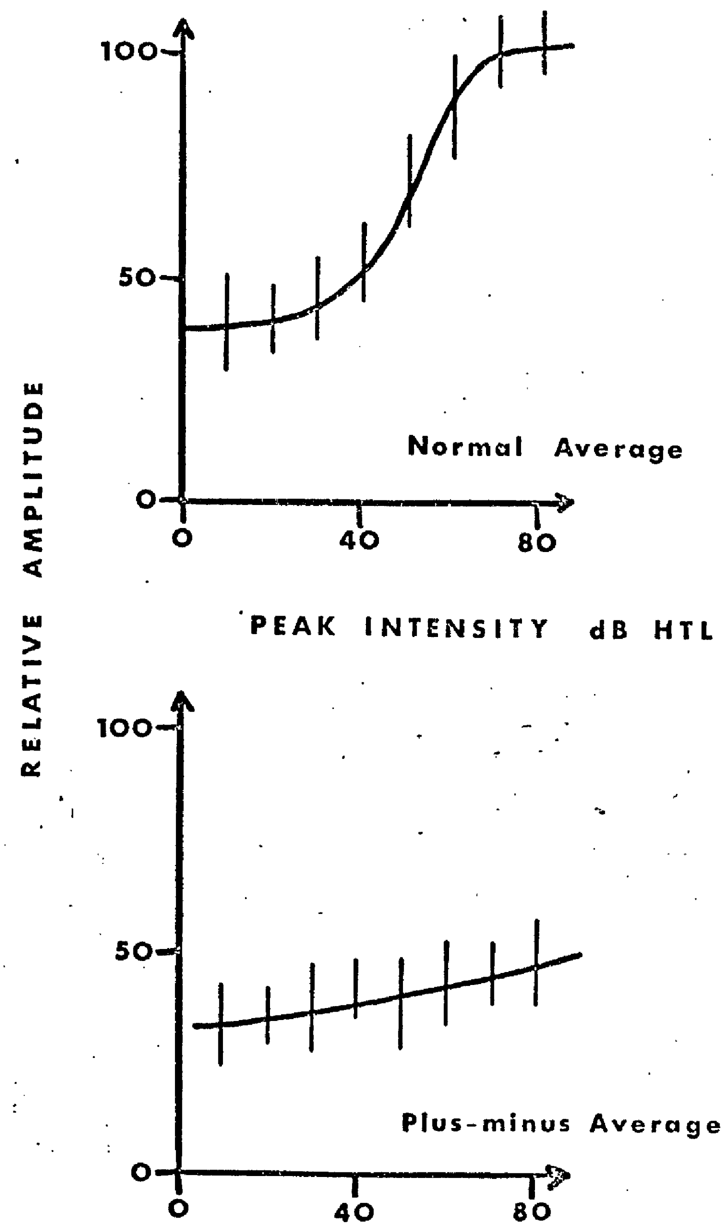


Figure 5.10 Grouped data for the first harmonic amplitude of the normal and plus-minus averages as a function of stimulus intensity.

Intensity dB HTL	t-value
80	8.61*
70	8.49*
60	5.60*
50	3.92*
40	2.36*
30	1.78
20	0.82
10	0.79
0	0.14

TABLE 5.VI

Statistical comparison of normal and plus-minus averages as a function of stimulus intensity for the principal subjects.

* Denotes a significant difference at the 95% level.

the principal subjects. The amplitude of the corrected first harmonic, and the second harmonic as a percentage of the first harmonic, taken at a modulation frequency of 11 Hz are shown in Table 5.VII. The first harmonic amplitudes are similar to those for the principal subjects (Table 5.1) and the proportion of the second harmonic is again in the range 10% to 20%. The results from the five children confirm that a modulation frequency of 11 Hz is applicable to all subjects.

b. Variation with modulation depth.

The response behaviour for the child subjects as the modulation depth is varied between zero and 10% is the same as reported for the principal subject group. The first harmonic amplitude saturates at a modulation depth of 5% and this appears to be the optimum setting to elicit a clear response.

c. Variation with carrier frequency.

The amplitude of the first and second harmonics decrease to about 50% of the maximum value as the carrier frequency is varied between 500 Hz and 4000 Hz. This behaviour is the same as reported for the main group of subjects.

d. Growth and decay of the response.

The parameters PS, PF and P50 defined previously, are determined for the five subjects and are shown in Table 5.VIII. Comparison of these values with the results from the principal group (Table 5.IV) shows them to be in the same range.

e. Variation with stimulus intensity.

The stimulus intensity is varied between zero and 80 dB HTL and the amplitude of the first harmonic for the normal average and for the plus-minus average is determined. The data for the five subjects are grouped together and a Student's t-test used to compare statistically the two averages as a function of modulation frequency. The resultant coefficients are shown in Table 5.IX. A response component may be shown to be statistically present at 30 dB HTL, compared with a detection

Subject	Amplitude of the First Harmonic μV	$F_2/F_1 \times 100\%$
C1	1.4	8
C2	1.9	17
C3	1.7	14
C4	2.1	17
C5	1.7	18

TABLE 5.VII

Response parameters for the subsidiary child subjects at the optimal stimulus parameters (Table 5.V).

Subject	PS	PF	P50
C1	300	1700	2900
C2	600	1900	2300
C3	400	1400	2200
C4	400	1700	2800
C5	600	1600	2900

TABLE 5.VIII

Parameters of response growth and decay for the subsidiary child subjects.

Intensity dB HTL	t-value
80	9.61*
70	8.72*
60	5.90*
50	4.10*
40	2.59*
30	2.38*
20	0.14
10	0.27
0	0.21

TABLE 5.IX

Statistical comparison of first harmonic amplitudes of the normal and plus-minus averages as a function of stimulus intensity for the subsidiary child group.

* Denotes a significant difference at the 95% level.

threshold of 40 dB HTL for the principal group.

5.9 Summary

The relationship between the parameters of the steady state response to a frequency modulated pure tone and the stimulus parameters has been investigated for a group of normal hearing adults and children.

The amplitude of the first harmonic as a function of modulation frequency is at a maximum around 11 Hz with a gradual fall off at lower and higher frequencies. This behaviour is the same for all subjects, whether they be adult or children, and a modulation frequency of 11 Hz is acceptable for each and every subject investigated. A marked contrast may be drawn between this relationship and the case for amplitude modulated stimulation, where the optimal modulation frequency is peculiar to each individual subject. The amplitude of the responses to frequency modulation are smaller than responses to frequency modulation (they are in the range 1 μV to 2 μV as opposed to 1.5 μV to 3.5 μV), but their harmonic distortion is much more stable. The proportion of the second harmonic as a percentage of the first harmonic at optimal conditions is in the range 10% to 20% for frequency modulation, whereas this range is 5% to 50% amplitude modulation. Also the responses to frequency modulation do not exhibit the rapid phase change around the response region which is found for amplitude modulated stimulation. As reported in Chapter 3, the response amplitudes from child subjects are on average slightly larger than from adults.

The amplitude of the first harmonic is found to saturate at modulation depths greater than 5% for a frequency modulated stimulus, while the second harmonic continues to increase with modulation depth. This behaviour is analogous to that for amplitude modulation where the first harmonic saturates above 60% modulation depth.

The behaviour of the first harmonic amplitude as a function of carrier frequency is the same as for amplitude modulation, being a maximum at

500 Hz and 1000 Hz, and falling to around 50% of its maximum at a carrier frequency of 4000 Hz. The second harmonic behaves in a similar manner.

Parameters to describe the growth and decay of the response with time are determined. They are found to compare well with those for amplitude modulation, whilst remembering that more inherent variability is expected in these parameters (than say carrier frequency) owing to the difficulty in standardising subject state.

The detectability of the response as a function of stimulus intensity has been investigated, and the analysis procedure is found to detect positive responses at 40 dB HTL for the principal group of subjects, and at 30 dB HTL for the subsidiary group of child subjects. Thus the responses to frequency modulation are less sensitive for threshold purposes than responses to amplitude modulation. This would be expected as the amplitudes are in fact smaller and would more quickly be dominated by residual EEG activity, as measured by the plus-minus average. A clinical assessment of the ability to predict behavioural threshold using frequency modulated stimulation is included in Chapter 6.

CHAPTER 6

Clinical Assessment using Frequency Modulated Stimulation.

6.1 Introduction

This chapter contains an assessment of the ability of steady state responses to frequency modulated stimulation, to estimate behavioural threshold, and therefore the place of these potentials in audiology. In the previous chapter, optimal conditions were determined for all stimulus parameters and these conditions were found to be applicable to all normal hearing subjects. This is in contrast to the situation for amplitude modulated stimulation, where the optimal modulation frequency requires determination for each individual subject.

The experiments previously described using frequency modulated stimulation were all conducted using binaural stimulation in normal hearing subjects. Therefore, before any clinical trials may be performed, the effect of monaural and binaural stimulation in normal and hearing impaired subjects requires investigation. The assessment of young children often requires that they be sedated, and the change in subject state (from that of reading quietly, used for previous experiments) could effect the response behaviour for different stimulus parameters. The effects of sedation also requires investigation therefore.

When the effects on the response behaviour have been determined, experiments are performed on groups of hearing impaired adults and children to determine the threshold of detection of the steady state responses to frequency modulated stimulation. These thresholds are compared with those for averaged EEG audiometry to transient stimulation (see Chapter 1), and also the behavioural thresholds, where these are available.

6.2 Effect of Subject State

The purpose of the experiments in this section is to determine the effect of sedation on response behaviour, when this is used to convert the subject state into a clinically acceptable form. The details of the analysis of subject state into the four sleep stages S1 to S4 (so is used to characterise the awake state) by analysis of the EEG components are described in Chapter 4.2. Briefly, each EEG section used to compile an average is characterised by a sleep stage index (SO, S1, S2, S3 or S4) and the average is then subjected to analysis into its harmonic components as described previously.

Experiments were performed using the cptimal stimulus parameters determined in Chapter 5, which are summarised in Table 5.V. The subjects were A, B, D and H from the principal group, who were volunteer members of hospital staff. Sleep was induced pharmacologically under clinical supervision, and on limited occasions recordings were made in natural sleep. No differences were observed in the responses to natural and drug induced sleep.

The behaviour of the response for variations in stimulus parameters in the different sleep stages is observed for the four subjects. The results from this series of experiments are summarised below:

(i) The stimulus parameters are set at the optimal values determined in Chapter 5. The effect of sleep stage on the smplitude of the corrected first harmonic is shown in Fig. 6.1 for the four subjects. The amplitude remains relatively constant in stages SO, S1 and S2, and then decreases rapidly in stages S3 and S4. The results are consistent both within and between the subjects, and so the data are collected and mean results for the four shown in Fig.6.2, which displays the variation with sleep state of the corrected first harmonic and also of the corrected second harmonic. The second harmonic amplitude falls rapidly even in stages S1 and S2, so that in these stages the harmonic distortion of the response is reduced.

These results are very similar to those obtained using amplitude modulated stimulation (Chapter 4.2) and are again encouraging from the point of view of audiological assessment. Good responses may be elicited

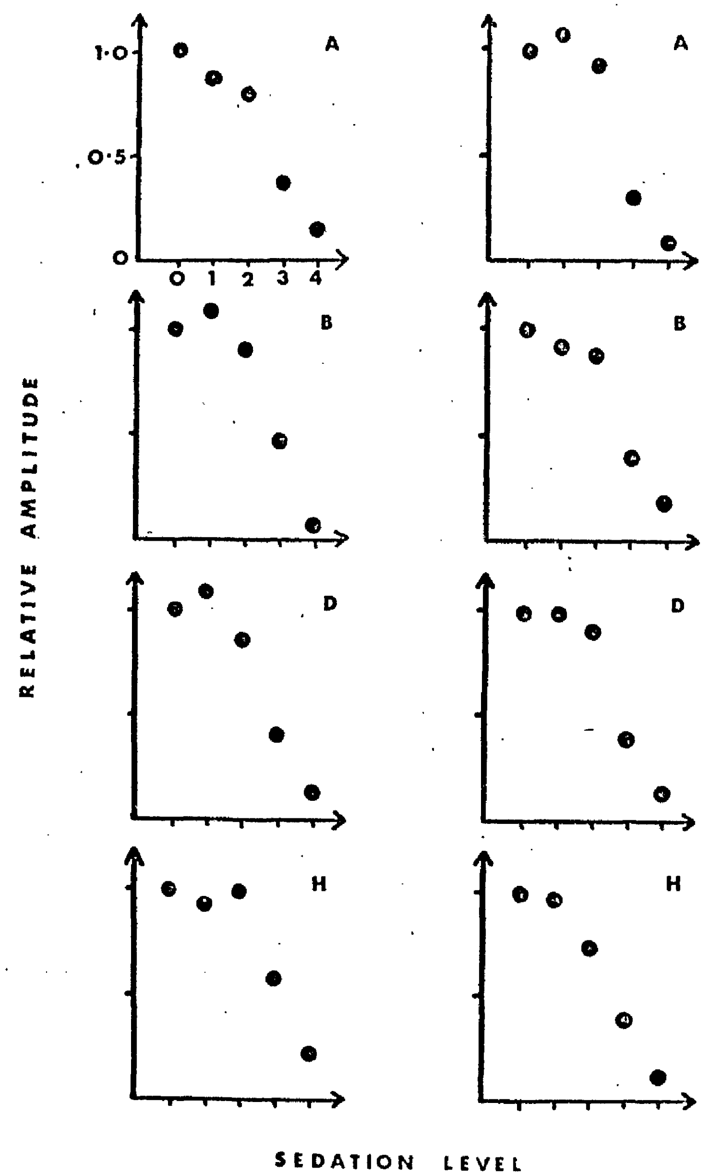


Figure 6.1 Examples of the variation of the amplitude of the corrected first harmonic with sleep stage.

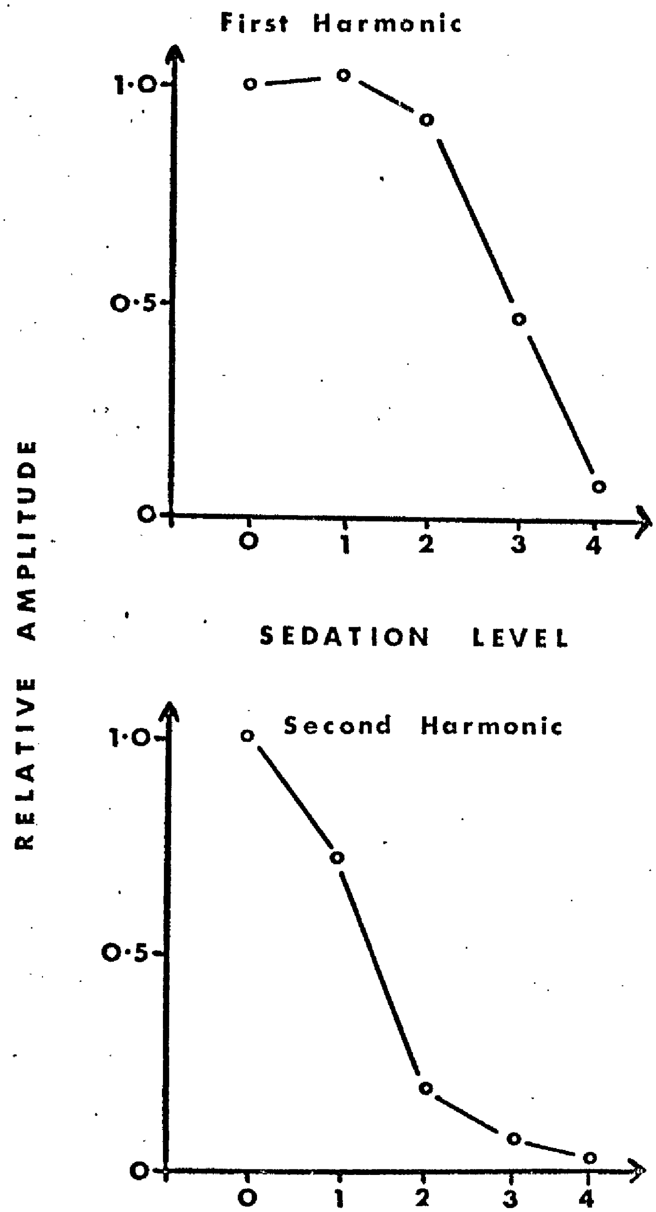


Figure 6.2 Grouped data for the amplitude of the corrected first and second harmonics as a function of sleep stage.

in stages S1 and S2 (where as a bonus the harmonic distortion is reduced) and these subject states adequately remove the difficulties experienced in dealing with children.

Further results are now quoted with the subjects in stage 2 to compare the effects of stimulus parameters in the awake and sedated states.

(ii) Experiments are performed in which the modulation frequency is varied between 5 Hz and 15 Hz for subjects A, B, D and H in sleep stage 2. The amplitude characteristic of the corrected first harmonic as a function of modulation frequency is very similar to that obtained in the awake state. A maximum response occurs around 11 Hz, and the response amplitude decreases gradually to about 50% of the maximum value as frequencies of 5 Hz and 15 Hz are approached. Table 6.I gives the mean amplitude at 11 Hz and the amplitude of the second harmonic as a percentage of the first harmonic. Comparison with Table 5.I and Table 5.II shows the similarity in first harmonic amplitude and the decrease in harmonic distortion at sleep stage 2. These results are very similar to the effects of subject state on the responses to amplitude modulated stimulation.

(iii) As the modulation depth is increased from zero to 10% the amplitude of the first harmonic saturates at about 5% modulation depth. This behaviour is the same as observed in the awake state.

(iv) The effect of carrier frequency as it is varied between 500 Hz and 4000 Hz is the same as in the awake state.

(v) The parameters characterising the growth and decay of the response may be expected to vary more with subject state than those describing the physical nature of the stimulus. Experiments are performed to determine the parameters PS, PF and P50 (which have been defined previously) by analysis of EEG sections equivalent to 100 cycles of modulation (Chapter 3.6). The means of a series of six determinations for each subject are shown in Table 6.II. Comparison with the equivalent

Subject	Amplitude of the First Harmonic uV	$\frac{F_1}{F_2}$ x 100%
A	0.9	4
B	0.8	6
D	1.2	7
H	1.6	2

Table 6.I

Response parameters at a modulation frequency of 11 Hz in sleep stage 2.

Subject	PS	PF	P50
A	400	1700	2100
B	600	1600	1900
D	400	1400	2100
H	500	1600	2300

<u>Table 6.II</u>

Parameters of response growth and decay of the corrected first harmonic in sleep stage 2.

parameters for the awake state given in Table IV indicates the similarity of the results, with a tendency towards a smaller value of the parameter P50.

(vi) The effect of stimulus intensity on the response behaviour is investigated. As before, the level at which a response is detectable is determined by performing a statistical comparison between the first harmonic amplitude of the normal average and the plus-minus average. The coefficients from the t-test used are shown in Table 6.III.

A maximum intensity of 60 dB HTL is used in an attempt to avoid awakening the subjects. Inspection of the table indicates statistical detection of the response at a stimulus intensity of 40 dB HTL. This result is similar to that obtained in the awake state.

The effects of stimulus variables for subjects in sleep stage 2 are found to be very similar to results obtained for the subjects in the awake state.

6.3 Monaural and Binaural Stimulation

The experiments described in this section were performed to determine the effects if any, of monaural, as opposed to binaural, stimulation, on the optimal stimulus parameters for response generation. The normal hearing subject A from the principal group and subject J (who has a 45 dB right perceptive hearing loss) are used for this determination.

Subjects A and J each participated in a series of four experimental sessions to investigate the response behaviour as a function of modulation frequency, modulation depth, carrier frequency and the number of samples used to compile the average, for the different modes of stimulation. The stimulus parameters determined in Chapter 5 (Table 5.V) were used for response generations, with a stimulus intensity 60 dB above behavioural threshold (that is 60 dB HTL for all cases except right ear stimulation

Intensity dB HTL	t-value
60	5.82 *
50	3.61 *
40	2.84 *
30	1.96
20	0.72
10	0.48
0	0.61

Table 6.III

Statistical comparison of normal and plus-minus averages as a function of stimulus intensity in sleep stage 2.

* denotes a significant difference at the 95% level

of subject J where 95 dB HTL is used). For right ear stimulation of subject J, appropriate masking is presented to the left ear. The results for the three different modes of stimulation are summarised below.

(i) The response behaviour is examined as the modulation frequency is varied between 5 Hz and 15 Hz, and is found to exhibit similar characteristics for the different modes of stimulus presentation. A maximum response is observed at around 11 Hz, while the response amplitude falls gradually to about 50% of the maximum value at modulation frequencies of 5 Hz and 15 Hz are approached. Table 6.IV gives the modulation frequency at which the corrected first harmonic is a maximum (the centre frequency), the response amplitude, and the second harmonic as a percentage of the first harmonic at the centre frequency. These parameters may be seen to be unaffected by the mode of stimulation. Phase characteristics are also the same with a linear relationship between the relative phase and the modulation frequency.

(ii) As the modulation depth of the stimulus is varied from zero to 10%, the first harmonic amplitude saturates at a modulation depth of 5% for both subjects using all modes of stimulation. Again no differences are observed in the response behaviour for right ear, left ear, or binaural presentation of the stimulus.

(iii) Experiments are performed using carrier frequencies in the range 500 Hz to 4000 Hz. For both subject A and subject J there are found to be no differences in the response behaviour as a function of carrier frequency for the three modes of stimulation. In all cases, the response is maximal at the lower frequencies, and falls to about 50% of the maximum at 4000 Hz.

(iv) The parameters PS, PF and P50, defined to characterise the growth and decay of the response, are investigated. Table 6.V shows the mean results of five determinations for each subject using each mode of stimulus presentation. The values obtained for the three parameters indicate no

Subject	Centre Frequency Hz	Amplitude uV	$\frac{F_2}{F_1} \times 100\%$
A (Binaural)	11.0	1.1	12
A (Left ear)	11.0	1.0	7
A (Right ear)	11.5	1.3	14
J (Binaural)	10.5	1.4	18
J (Left ear)	11.5	1.3	16
J (Right ear)	11.5	0.9	14

Table 6.IV

Response parameters for monaural and binaural stimulation for subject A (normal hearing) and subject J (45 dB right perceptive loss at 1000 Hz).

Subject	PS	PF	P50
A (Binaural)	500	1500	2300
A (Left ear)	400	1600	2600
A (Right ear)	500	1900	2400
J (Binaural)	300	1400	2800
J (Left ear)	600	1600	2600
J (Right ear)	400	1600	2300

Table 6.V

Parameters of response growth and decay of the corrected first harmonic for monaural and binaural stimulation of subject A (normal hearing) and subject J (45 dB right perceptive loss at 1000 Hz) dependence on the way the stimulus is presented.

Thus, there are found to be no differences in response behaviour as a function of stimulus parameters between left ear, right ear and binaural stimulation. The relationship between response amplitude and stimulus intensity for an ear with hearing loss is investigated as part of the experiments to determine threshold.

6.4 Threshold Determination in Adults

With a knowledge of the effects of subject state and stimulus presentation on the behaviour of steady state responses to frequency modulated stimulation, an assessment of the ability of these responses to predict behavioural threshold is performed. A group of ten adult clinical subjects with various degrees of hearing loss in either ear are selected. All knowledge regarding the outcome of other assessments is witheld from the investigator, who determines the threshold of the steady state responses at 1000 Hz for each subject in either ear. The transient response thresholds to tone burst stimulation at 1000 Hz are also determined for comparison. Finally the results may be compared with the behavioural thresholds obtained using conventional audiometry. The ten adult subjects are labelled A11 to A20 in order to distinguish them from the ten subjects used for the amplitude modulation experiments in Chapter 4. The same subjects were not used for the two sets of experiments because of attendance difficulties.

Unlike the determinations using amplitude modulated stimulation, the modulation frequency does not require determination for each individual, and all experiments may be performed using one set of stimulus parameters, which have been given in Table 5.V.

A series of experiments is performed for each ear, with appropriate masking delivered to the contralateral ear, commencing at a stimulus intensity which is comfortably loud to the subject. The stimulus is progressively decreased in steps of 10 dB until the "steady-state threshold" is reached. This is taken as the level at which no response component is present (i.e. the level at which no difference may be detected between the normal average and the plus-minus average). Again it may be emphasised that this procedure involved no value-judgement on behalf of the investigator as the only criterion is the statistical comparison of two averages.

Table 6.VI shows the steady state thresholds for the ten subjects as determined by the above method. For left ear stimulation of subject A,13 no response was detectable at a stimulus intensity of 110 db HTL, and no responses in either ear were detectable for subject A14.

Transient response thresholds are obtained by performing averaged EEG audiometry to tone burst stimulation (see Chapter 1), and these results are given in Table 6.VII. If Tables 6.VI and 6.VII are compared, the transient response thresholds may be seen to be more sensitive.

The behavioural pure tone thresholds at 1000 Hz are determined by conventional audiometry and are shown in Table 6.VIII. Comparison of the steady state thresholds and the behavioural thresholds clearly shows that the steady state determination over estimates the hearing loss by about 40 dB.

If a linear correlation is performed between the steady state and the behavioural thresholds, which indicates the consistency of this over-estimation. A linear regression analysis between the two sets of data yields the relationship

$$B = 0842S - 27.8$$

where B is the behavioural threshold and S is the steady state threshold in dB HTL.

The time saved (something in excess of 20 minutes) by not having to

Subject	Steady State Threshold dB HTL	
	Left ear	Right ear
A11	100	90
A12	50	70
A13	-	80
A14	-	-
A15	60	40
A16	90	100
A17	110	50
A18	40	70
A19	90	50
A20	80	110

TABLE 6.VI

Steady state thresholds at 1000 Hz for the 10 adult clinical subjects.

Subject	Transient Response Threshold db HTL	
	Left ear	Right ear
A11	80	50
A12	30	50
A13	110	50
A14	100	100
A15	30	30
A16	50	70
A17	70	10
A18	10	60
A19	50	30
A20	40	90

TABLE 6.VII

Transient response thresholds at 1000 Hz for the 10 adult clinical subjects.

Subject	Behavioural Threshold dB HTL	
	Left ear	Right ear
A11	65	45
A12	20	30
A13	90	35
A14	95	85
A15	20	10
A16	45	55
A17	60	10
A18	0	40
A19	40	20
A20	35	75

TABLE 6.VIII

Behavioural thresholds at 1000 Hz for the 10 adult clinical subjects.

determine the optimal modulation frequency for each subject may be used to extend the range of each clinical session. Two of the subjects (A13 and A18) participated in extended experiments in which steady state thresholds were determined at frequencies of 500 Hz, 2000 Hz and 4000 Hz in each ear, as well as at 100 Hz. The linear relationship derived above may then be used to predict the behavioural threshold from the steady state threshold. In this way, it may be possible to compensate for the overestimation of the hearing loss by the steady state determination.

Table 6.IX gives the steady state thresholds, the behavioural thresholds, and the predicted behavioural thresholds for subject A13. In cases where no steady state response is detectable at 110 dB HTL, the only prediction available regarding the behavioural threshold, is that it is in excess of 65 dB HTL (the level predicted by a steady state value of 110 dB HTL). The value of the prediction may be seen from inspection of Table 6.IX.

Similarly Table 6.X shows a comparison of the different thresholds obtained from subject A18. Again the use of the linear relationship can improve the estimation of the behavioural threshold.

6.5 Threshold Determination in Children

The efficiency of threshold determination, from steady state responses to frequency modulation, is investigated in children. A group of ten children (labelled C11 to C20, to distinguish them from the group investigated with amplitude modulation) aged between 2 years and 8 years, all of whom were difficult to test using conventional audiometry were assessed. The clinical difficulties were such that in 5 of the cases, behavioural thresholds could not be obtained. Indeed this is the very class of patient for whom electrophysiological techniques are required.

All the children were sedated to make their behaviour clinically acceptable, and all responses were obtained in sleep stage 2. A series

Threshold dB HTL	Frequency Hz			
	500	1000	2000	4000
Left Ear Steady State	100	-	-	-
Behavioural	60	90	100	110
Predicted	56	65+	65+	65+
Right Ear Steady State	70	80	80	100
Behavioural	30	35	35	40
Predicted	31	39	39	56

TABLE 6.IX

Comparison of thresholds for Subject A13.

Threshold dB HTL	Frequency Hz			
	500	1000	2000	4000
Left Ear Steady State	30	40	60	50
Behavioural	0	0	10	15
Predicted	-3	6	22	14
Right Ear Steady State	40	70	90	110
Behavioural	20	40	50	70
Predicted	6	31	48	65

TABLE 6.X

Comparison of thresholds for Subject A18.

of experiments was performed in a similar manner as described in the preceding section for the adult subjects. For each subject the steady state, transient, and behavioural thresholds at 1000 Hz are determined in each ear. Table 6.XI shows the steady state thresholds for the ten child subjects. This threshold is taken as the lowest intensity level (in 10 dB steps) at which a response component is detectable. For subject C14 (left ear) subject C17 (both ears), and subject C20 (left ear) no response is detectable at a stimulus level of 110 dB HTL. These steady state thresholds may be compared with the electrophysiological thresholds to tone burst stimulation given in Table 6.XII. As with the adult subjects, the steady state thresholds are consistently higher.

For subjects C11, C14, C15, C18 and C20, it was possible to determine reliable behavioural thresholds using conventional audiometric techniques, and the results are shown in Table 6.XIII. Comparison of Tables 6.XIII and 6.XI indicates that, as with the adult subjects, the steady state technique overestimates the hearing loss by about 40 dB.

As before, a linear relationship between the behavioural threshold and the steady state threshold may be derived. A linear correlation and regression analysis yields a coefficient of correlation of 0.973 and a relationship between the thresholds of :

$$B = 0.720S - 18.9$$

where B is the behavioural threshold and S the steady state threshold in dB HTL.

In three of the subjects (C11, C14 and C18), steady state thresholds were also determined at 500 Hz, 2000 Hz and 4000 Hz. Again this is possible because of the time saved by not having to determine the optimal modulation frequency for each subject. However, the time taken for this full evaluation does become considerable, and the implications of this are discussed further in Chapter 8.

As before, the linear relationship between the thresholds may be used

Subject	Steady State Threshold dB HTL	
	Left ear	Right ear
C11	50	90
C12	70	30
C13	60	70
C14	-	100
C15	110	50
C16	40	80
C17	-	-
C18	50	80
C19	70	110
C20	-	110

TABLE 6.XI

Steady state thresholds at 1000 Hz for the 10 child clinical subjects.

Subject	Transient Threshold dB HTL	
	Left ear	Right ear
C11	30	60
C12	60	30
C13	70	40
C14	110	70
C15	80	30
C16	20	60
C17	100	90
C18	50	40
C19	50	90
C20	40	80

TABLE 6.XII

Transient response thresholds at 1000 Hz for the 10 child clinical subjects.

Subject	Behavioural Threshold dB HTL	
	Left ear	Right ear
C11	20	45
C12	-	-
C13	-	-
C14	90	60
C15	60	20
C16	-	-
C17	-	-
C18	15	30
C19	-	-
C20	75	60

TABLE 6.XIII

Behavioural thresholds at 1000 Hz for the 10 child clinical subjects.

to predict the behavioural threshold. A comparison for different stimulus frequencies is performed between the steady state threshold, the behavioural threshold and the predicted threshold. The results for subjects C11, C14 and C18 are given in Tables 6.XIV, 6.XV and 6.XVI respectively. Where no response is detectable at 110 dB HTL (subject C14 for 2000 Hz and 4000 Hz in both ears and 1000 Hz in left ear), the only information available regarding the predicted threshold is its minimum value computed from the 110 db HTL value.

Inspection of the results in the three tables shows both the over-estimation of the hearing loss from the steady state threshold alone, and the compensatory effect of using the linear relationship to predict the behavioural threshold. The prediction appears to be less accurate at 4000 Hz and this may be due to the diminished response amplitude at this frequency.

6.6 Summary

In some subjects, notably young children, sedation is required to reduce their activity to a clinically acceptable level. The effect of subject state, in terms of sleep stages, on the behaviour of the steady state responses to frequency modulated stimulation has been investigated. The response amplitude for sleep states S1 and S2 is similar to the amplitude in the awake state, while at deeper stages of sleep the amplitude is greatly diminished. Thus sleep states 1 and 2 are suitable for clinical assessment. The response behaviour to stimulus parameters such as modulation frequency, modulation depth, carrier frequency and the number of samples used to compile the average, does not change with sedation. This behaviour is the same as the behaviour of responses to amplitude modulated stimulation, and once again is a significant advantage over transient stimulation where the response waveform and threshold can change in sleep.

There are no detectable differences in the response behaviour whether

Threshold dB HTL	Frequency Hz			
	500	1000	2000	4000
<u>Left Ear</u> Steady State	40	50	60	80
Behavioural	15	20	20	15
Predicted	10	17	17	38
<u>Right Ear</u> Steady State	80	90	90	110
Behavioural	40	45	50	60
Predicted	38	46	46	65

TABLE 6.XIV

Comparison of thresholds for Subject C11.

Threshold dB HTL	Frequency Hz			
	500	1000	2000	4000
Left Ear Steady State	100	-	-	-
Behavioural	50	90	90	110
Predicted	53	60+	60+	60+
Right Ear Steady State	70	100	-	-
Behavioural	30	60	90	110
Predicted	31	53	60+	60+

TABLE 6.XV

Comparison of thresholds for Subject C14.

Threshold dB HTL	Frequency Hz			
	500	1000	2000	4000
<u>Left Ear</u> Steady State	50	50	50	70
Behavioural	10	15	15	20
Predicted	17	17	17	31
<u>Right Ear</u> Steady State	60	80	70	80
Behavioural	20	30	30	20
Predicted	24	38	31	38

<u>TABLE 6.XVI</u>

Comparison of thresholds for Subject C18.

the stimulus is presented binaurally or monaurally for both normal hearing and hearing impaired subjects. Thus one set of stimulus parameters is sufficient to elicit responses in all cases.

The ability to predict behavioural threshold from the steady state threshold has been investigated in ten adults and ten children. For both adults and children the steady state threshold overestimates the hearing loss by about 40 dB, but when the two sets of thresholds are subjected to linear correlation they yield coefficients of 0.960 for the adults and 0.973 for the children. This indicates the consistency of the steady state threshold determination. Linear relations between the steady state and behavioural thresholds may be determined for both the adults and the children, and this may be used to predict the behavioural threshold from the steady state threshold.

CHAPTER 7

Relations between Steady State Responses, Transient Responses, and the EEG.

7.1 Introduction

Previous chapters have discussed the behaviour of steady state responses to both amplitude and frequency modulation as a function of stimulus parameters. The ability of these potentials to predict auditory threshold has also been investigated. This chapter seeks to present evidence regarding the nature and origins of steady state responses, and compares the properties of these potentials with the properties of evoked potentials to transient stimulation, and of the electroencephalogram (EEG) itself.

The behaviour of the steady state and transient responses as a function of carrier frequency may be directly compared, as may the parameters which are used to characterise the growth and decay of the two types of response.

One comparison between steady state responses and both transient responses and the EEG may be performed by an investigation of the spatial distribution of these different electric potentials over the scalp surface. Some inferences may also be drawn from a comparison of the response regions in the modulation frequency domain (for in particular amplitude modulated stimulation) with the power spectral density of the EEG.

Some preliminary information regarding the origins of steady state responses is reported from experiments performed on two guinea pigs in the awake and anaesthetised state.

7.2 Steady State and Transient Responses

A first step in the comparison of the two classes of response is to investigate their behaviour as a function of carrier frequency. The results for steady state responses to both amplitude and frequency modulated stimulation have been quoted in the preceding chapters. Experiments have been performed for both methods of stimulus presentation, in adults and in children, for the awake state and also under sedation, at carrier frequencies of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. In all cases the response behaviour is the same. Maximum responses are obtained at a frequency of 500 Hz or 1000 Hz, while at 4000 Hz the response amplitude falls to about 50% of the maximum value. Also the phase of the first harmonic is found to remain constant as the carrier frequency is varied for all experiments.

A series of experiments was performed on subjects A, B, D and H, in which the effect of carrier frequency on the averaged EEG responses (AEA) to tone burst stimulation is investigated. The Medelec evoked response system was used to obtain these AEA responses at frequencies of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz, using a stimulus intensity of 70 dB HTL presented binaurally. The technique of averaged EEG audiometry has been described in Chapter 1. Fig. 7.1 shows the variation of the peak to peak amplitude of the N1 and P2 components (see Fig. 1.1) as a function of carrier frequency, from four determinations at each frequency for each subject. The results are expressed in terms of relative amplitude to account for the differences in absolute amplitudes achieved for the different subjects. The behaviour is seen to be very similar to that for the steady state responses. Also the form of the response is found to be the same at different frequencies (i.e. there is no appreciable latency shift of the components). Thus the behaviour of the transient responses and both classes of steady state response is identical.

The growth and decay of the steady state responses has been investigated for different stimulus parameters and subject states. In all cases the amplitude increases rapidly as the stimulus is applied, reaches a plateau level, and then gradually decreases with continuing stimulation. The parameters PS (number of cycles of modulation to start of plateau), PF

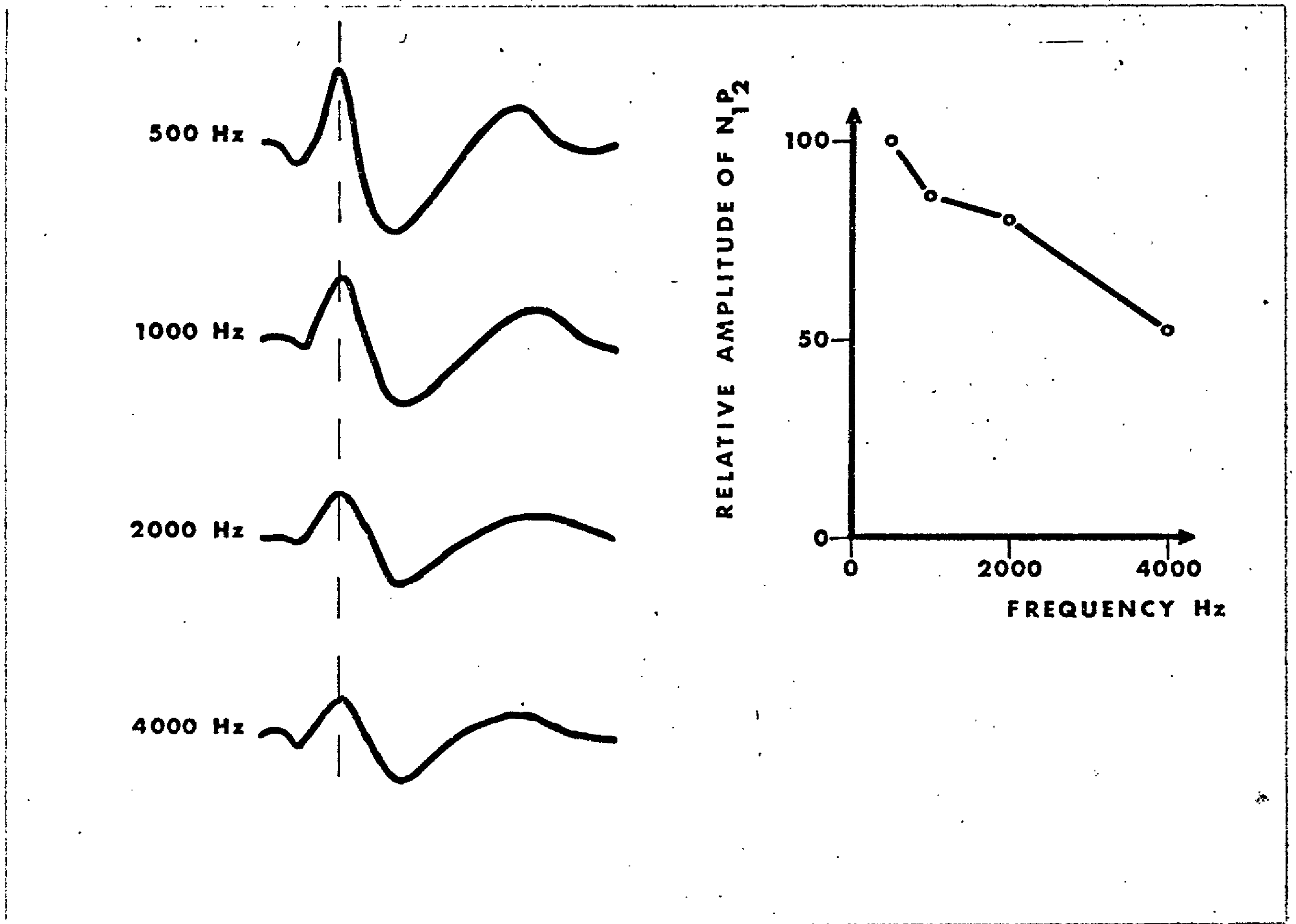


Figure 7.1 Effect of carrier frequency on the transient response.

(number of cycles to end of plateau) and P50 (number of cycles to point where response is 50% of the maximum value) are used to characterise this behaviour. Typical values for these parameters for all forms of the steady state responses are found to be:- PS=500, PF=1800 and P50=2500. It is worth noting again that these parameters are expressed in terms of number of cycles of modulation applied, and not absolute time, to obtain consistent results between subjects when different modulation frequencies are used.

A series of experiments was performed on subjects A, B, D and H to investigate the growth and decay of transient responses. The following stimulus parameters were used:-

(i) Stimulus intensity = 70 dB HTL.

(ii) Stimulus frequency = 1000 Hz.

(iii) Binaural presentation.

(iv) Inter-stimulus interval = 2 sec.

(v) Number of stimuli presented = 300.

(vi) Tone burst duration = 330 msec.

(vii) Tone burst rise/fall time = 20 msec.

The peak to peak amplitude of the N1 and P2 response components is used to characterise the response amplitude, and the responses are averaged in blocks, each of which contains 10 samples (i.e. average 1 contains samples 1 to 10, average 2 contains samples 11 to 20, etc). The growth and decay curve is similar to that for steady state responses, with an early plateaux and gradual decay. For the transient responses the plateau is reached much more quickly than for steady state responses. The parameters NS (number of stimuli to start of plateau), NF (number of stimuli to end of plateau) and N50 (number of stimuli to point where response is 50% of maximum value) are used to characterise the growth and decay of the transient response, and mean results from five experiments on each of the four subjects are given in Table 7.I. Inspection of Table 7.I shows that the maximum amplitude is reached in the first few stimuli presented to

Subject	NS	NF	N50
A	0	70	180
B	0	130	290
D	0	110	220
H	0	60	190

TABLE 7.I

Parameters of response growth and decay for tone burst stimulation.

NS = Number of stimuli to start of plateau.

NF = Number of stimuli to end of plateau.

N50 = Number of stimuli to point where response falls to 50% of the maximum value.

the subject. This behaviour is unlike that for steady state responses, where an "entrainment period" of about 500 cycles of modulation (50 seconds at a modulation frequency of 10 Hz) is required before the response reaches its maximum value. Also, the parameters NF and N50 exhibit considerably more inter-subject variation than the equivalent parameters (PF and P50) for the steady state responses. This effect may be due to the greater difficulty in maintaining a constant level of attention to a stimulus which is presented intermittently, than to a constantly applied stimulus.

The period of "entrainment" that the system requires before the maximum steady state response is achieved raises the possibility that a similar period of "facilitation" may exist after the acoustic stimulus is removed. To test this possibility, experiments were performed on Subjects A and D in which recordings were made after the removal of the stimulus during the plateau period. Five measurements were made on each subject, and in no case was any difference detectable between the normal average and the plus-minus average. Thus no response was detected, indicating the absence of any "running-on of a learned oscillator".

The analysis of transient responses in the time domain (i.e. in terms of the amplitude and latency of the components) and of steady state responses in the frequency domain (i.e. in terms of the amplitude and phase of the Fourier components) may be tentatively compared by making certain oversimplified assumptions about the system. Examples of the phase characteristic as a function of modulation frequency have been given in Chapter 3 for amplitude modulated stimulation. Fig. 3.1 (Subject A) shows the phase characteristic for a single response region, and Fig. 3.5 (Subject D) shows the phase characteristic for a dual response region. These may be interpreted as consisting of two different phase shifts. One phase shift increases linearly with increasing frequency, and may be seen in the regions where response amplitude is not changing rapidly with modulation frequency. An extra phase shift of about 180 degrees appears to occur around the regions of peak response, and is ascribed to a band pass filter in the system. A transmission line with a constant time delay exhibits a linear phase characteristic with frequency, and so the system is assumed to consist of such a transmission line plus a band pass filter (43, 44).

It is now possible to estimate both the constant time delay and the "apparent latency" of the evoked potential at the point where the response amplitude changes rapidly with modulation frequency (41).

The constant delay τ is given by:-

$$\tau = \frac{\Delta\phi}{\Delta f . 360}$$

where $\frac{\Delta\phi}{\Delta f}$ is the linear phase gradient.

The computed latency T is given by

$$T = \tau + \frac{1}{360} \cdot \frac{\delta\phi}{\delta f}$$

where $\frac{\delta\phi}{\delta f}$ is the phase gradient around the response region. Thus the constant delay τ and the computed latency T are calculated for the responses to amplitude modulated stimulation.

For the responses to frequency modulated stimulation, there is no clear separation of the phase characteristic, as the response amplitude changes only gradually with modulation frequency and is broadly linear between 5 Hz and 15 Hz. Here an estimate of the latency is made from:-

$$T = \frac{1}{360} \cdot \frac{\Delta\phi}{\Delta f}$$

where $\frac{\Delta\phi}{\Delta f}$ is the mean phase gradient between 5 Hz and 15 Hz.

Table 7.II shows the time delays, τ, for each of the ten members of the principal group. These results are computed from the data collected for the experiments described in Chapter 3. There is a considerable degree of variability in the values, which may be seen to range from 20

Subject	Time Delay τ msec
A	20.5
B	30.4
C	24.1
D	27.8
E	39.6
F	80.4
G	61.2
H	21.4

TABLE 7.II

Calculated time delays for amplitude modulated stimulation.

msec to 80 msec. Rodenburg et al (44) have reported a value of 66 msec from one human subject, but no data are available on the range of values to be expected. Tielen et al (43) obtained values of 34 msec and 43 msec from two unanaesthetised dogs.

Table 7.III shows the computed latencies for the response regions for Subjects A to H. For the subjects who exhibit two response regions in the modulated frequency domain, there will of course be two values of computed latency. Inspection of Table 7.III again indicates a large degree of variation of the results. However, all the values obtained (with the possible exception of Subject H), fall in a range which could correspond to a component of the transient evoked potential.

The calculated latencies for frequency modulated stimulation of the ten subjects are shown in Table 7.IV. The results all fall in the range 109 msec to 148 msec, and this greater degree of similarity may reflect the greater consistency in the response characteristics as a function of modulation frequency for frequency modulation, than for amplitude modulation.

Thus a series of somewhat drastic assumptions may be made to enable the characteristics of steady state responses to be expressed in terms of apparent latencies in the time domain.

7.3 Steady State Responses and the EEG

In the previous section the presence of a band pass filter is postulated to account for the sharp dependence of the response amplitude on modulation frequency. Steady state potentials evoked by visual stimulation exhibit a similar frequency dependence (41), and evidence exists that a number of the response characteristics are closely related to corresponding characteristics of the spontaneous EEG (50). In particular, the centre frequency of the response region with modulation frequency is found to vary from subject to subject, but corresponds closely to the alpha frequency of the subject's spontaneous EEG. If the

Subject	Calculated Latency T_1 msec	Calculated Latency T_2 msec
A	141	-
B	129	-
C	90	-
D	143	308
E	262	169
F	242	168
G	238	149
H	410	-

TABLE 7.III

Computed latencies for amplitude modulated stimulation.

Subject	Calculated Latency T msec
A	126
B	109
C	144
D	129
E	118
F	136
G	148
H	129

TABLE 7.IV

Computed latencies for frequency modulated stimulation.

auditory steady state responses behave in the same way, the subject's EEG may be used to predict the optimal modulation frequency and so remove one of the drawbacks of amplitude modulated stimulation.

In Chapter 3, linear correlations were performed between the amplitude of the corrected first harmonic (response) and the amplitude of the plus-minus first harmonic (residual EEG), and no significant relationship was detected. In this section the envelope of the response region in modulation frequency (amplitude of the corrected first harmonic) for amplitude modulation, is correlated with the power spectral density of the spontaneous EEG. The envelope of the response region is available for each subject from Chapter 3. Fifty sections of spontaneous EEG, each of length four seconds, are used to compile the power spectral density of the EEG. These EEG sections were available from the recordings made for Chapter 3 between the periods of acoustic stimulation. Each section of EEG is transformed into the frequency domain using the Fast Fourier Transform and Display programme on the PDP 12 computer. The fifty sections for each subject are averaged to give the mean spectral density for each member of the principal subject group. Examples of the response envelope and the frequency content of the EEG are illustrated schematically in Fig. 7.2. The EEG spectra did not exhibit a sharp peak at the alpha frequency, as no attempt was made to use EEG sections in which alpha activity was evident.

A linear correlation is then performed between the response envelope and the spectral content of the EEG for modulation frequencies between 5 Hz and 15 Hz. The resultant correlation coefficients are given in Table 7.V, and they may be seen not to express any significant relationship between the two variables.

The experiment was repeated using only sections of spontaneous EEG which contain alpha activity to form the spectral content of the EEG. The correlation coefficients are shown in Table 7.VI and still do not reveal any significant relationship. Thus it is not possible to predict

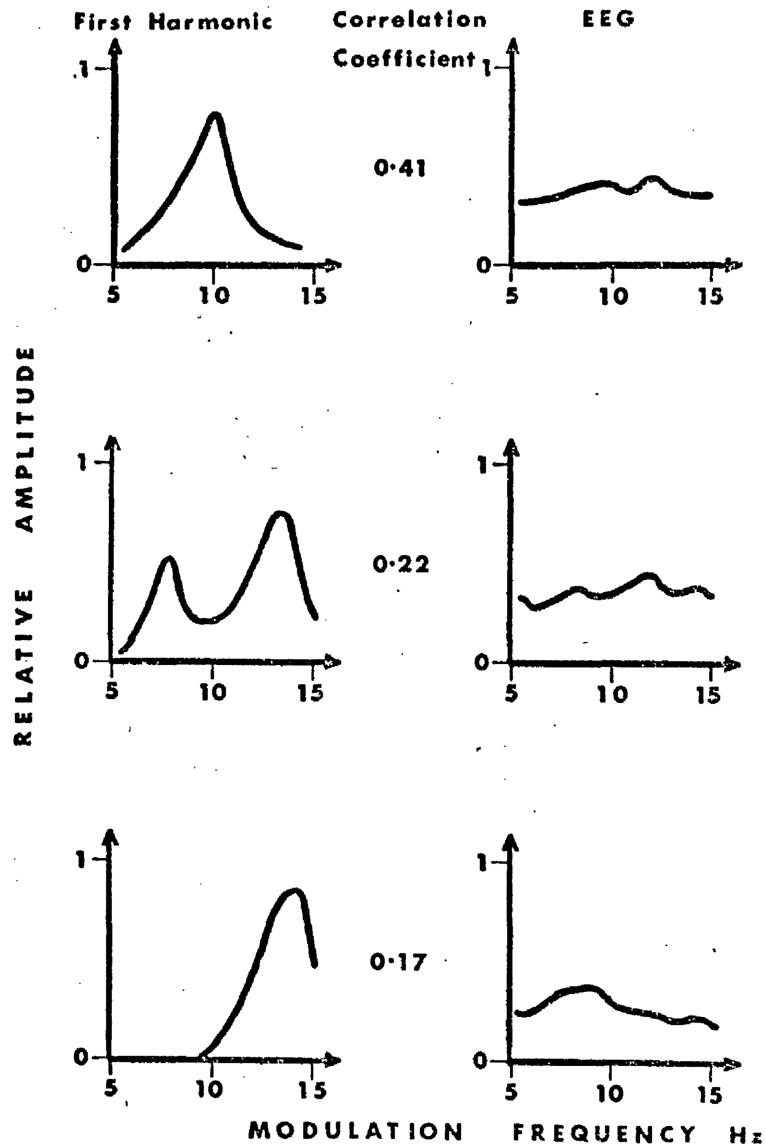


Figure 7.2 Examples of the response envelope and the spectral content of the EEG.

Subject	Correlation Coefficient
A	0.41
B	0.09
C	0.17
D	0.34
E	0.26
F	0.14
G	0.22
H	0.31

TABLE 7.V

Linear correlation between the response envelope and the spontaneous EEG.

Subject	Correlation Coefficient
A	0.32
B	0.24
C	0.31
D	0.24
E	0.36
F	0.21
G	0.27
H	0.13

TABLE 7.VI

Linear correlation between the response envelope and the spontaneous EEG during alpha activity.

the response region from the spontaneous EEG, and the problem of predicting the optimal frequency for amplitude modulation remains.

7.4 Spatial Distribution of Responses

Variations in the spatial distribution over the scalp surface for different responses may indicate possible differences in their sites of origin. These spatial contour maps are obtained by recording from multiple electrode sites on the scalp. The use of the Offner electroencephalograph and Ampex SP2000 tape recorder mentioned in Chapter 2, enables seven simultaneous EEG channels to be processed. The averaging programme for the PDP12 computer is modified to deal with the seven simultaneous inputs, and each of the seven channels is then analysed into its harmonic components as described previously.

The ten-twenty electrode system (51) is used to locate the electrodes on the scalp surface in a reproducible manner. This system is illustrated diagrammatically in Fig. 7.3. The seven channels of EEG are still not sufficient to construct a full contour map using only one set of electrode positions. Three types of recording, labelled T1, T2 and T3 are defined, each of which contains the vertex electrode (Cz). The different recordings may then be related to each other via the vertex electrode. The three types of recording are defined below:-

<u>Type T1</u> contains the electrodes Cz, F3, F4, P3, P4, T3 and T4.

<u>Type T2</u> contains the electrodes Cz, Fz, Pz, C3, C4, O1 and O2.

<u>Type T3</u> contains the electrodes Cz, T5, T6, F7, F8, Fp1 and Fp2.

All recordings are referred to mid-line on the forehead.

Subjects A and D were used for the spatial distribution experiments. Each subject participated in recordings for five sessions of types T1, T2 and T3. The optimal stimulus parameters determined for each subject in Chapter 3 were used for amplitude modulation, and in Chapter 5 for frequency modulation. A stimulus intensity of 70 dB HTL was presented binaurally in all cases.

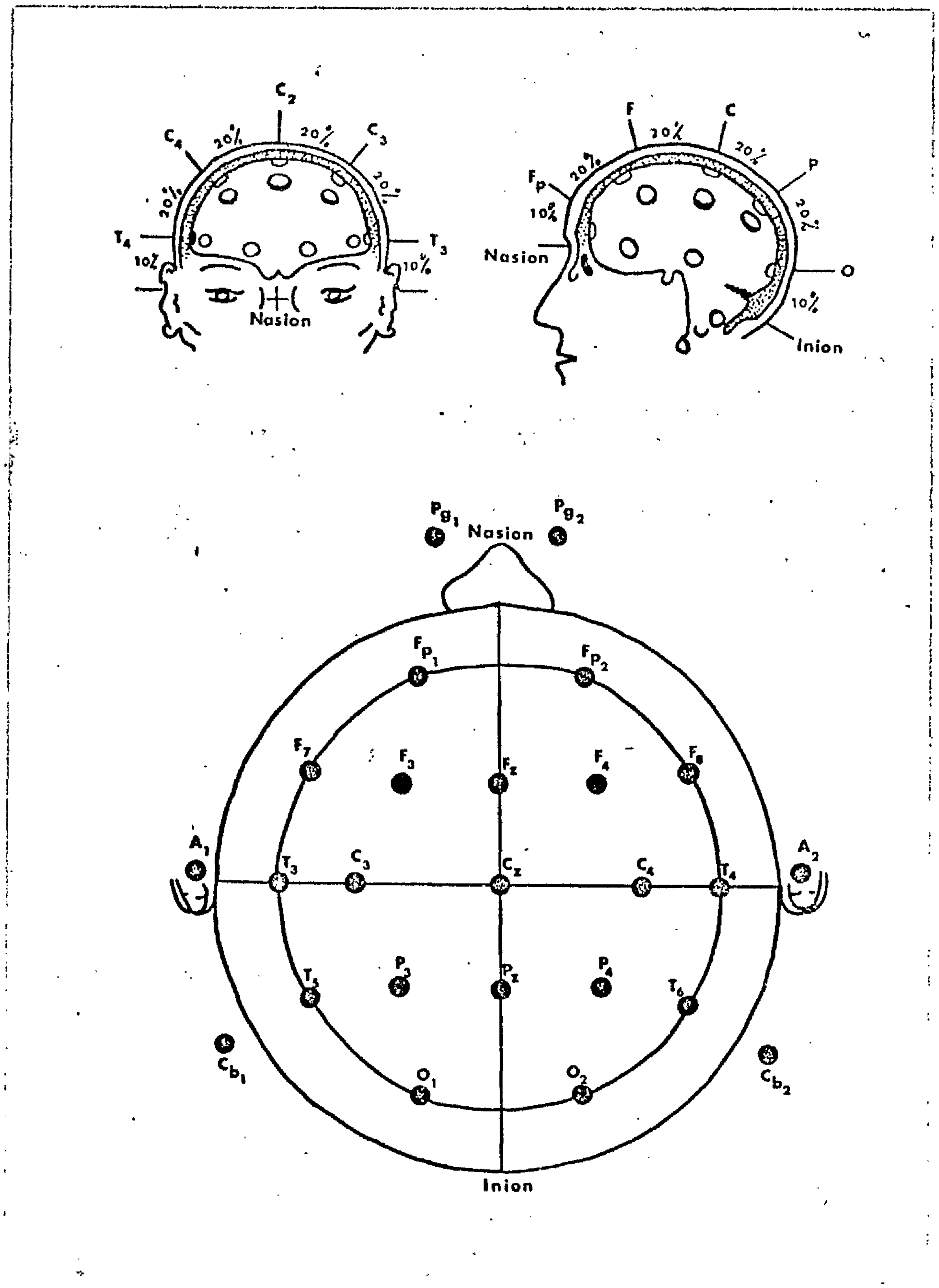


Figure 7.3 The ten-twenty electrode system.

The means of the three recording types are related for each subject by arbitrarily setting the values for electrode Cz to be equal, and of value 100 units. A contour map may then be constructed by linear extrapolation between the values for each electrode. The distributions for the two subjects are found to be similar and therefore the data are grouped together to produce a mean distribution. This procedure is used for the first and second harmonic amplitudes, for responses to both amplitude and frequency modulated stimulation.

Fig. 7.4 shows diagrammatically the spatial distribution of the first and second harmonic amplitudes for amplitude modulated stimulation, and Fig. 7.5 shows the results for frequency modulated stimulation. It may be seen that the two sets of distributions are very similar. For both types of stimulation the responses are maximal at the vertex, with the amplitudes falling more rapidly towards the front and rear sections of the skull than for the lateral portions. A limited series of experiments showed no differences in distribution for monaural stimulation.

Fig. 7.6 shows the spatial distribution of evoked responses to transient stimulation for both the visual and auditory responses. The data for visual stimulation are for the P200 component and are constructed from Donchin and Lindsley (36), while the auditory data are constructed from Vaughn and Ritter (52) for the P2 component. Comparison of Figs. 7.4, 7.5 and 7.6 clearly indicates the similarity in the distribution of transient auditory evoked responses and both forms of steady state responses to auditory stimulation.

The data for visual stimulation are included as a contrast, and this distribution indicates the location of the visual cortex in the occipital region. Fig. 7.7 shows the spatial distribution of the alpha activity, constructed from Hill and Parr (53). The difference in distribution of all the auditory responses from the alpha activity is clear, while the visual response and the alpha activity both exhibit an appreciable amplitude over the occipital region. This may reflect the close relationship between

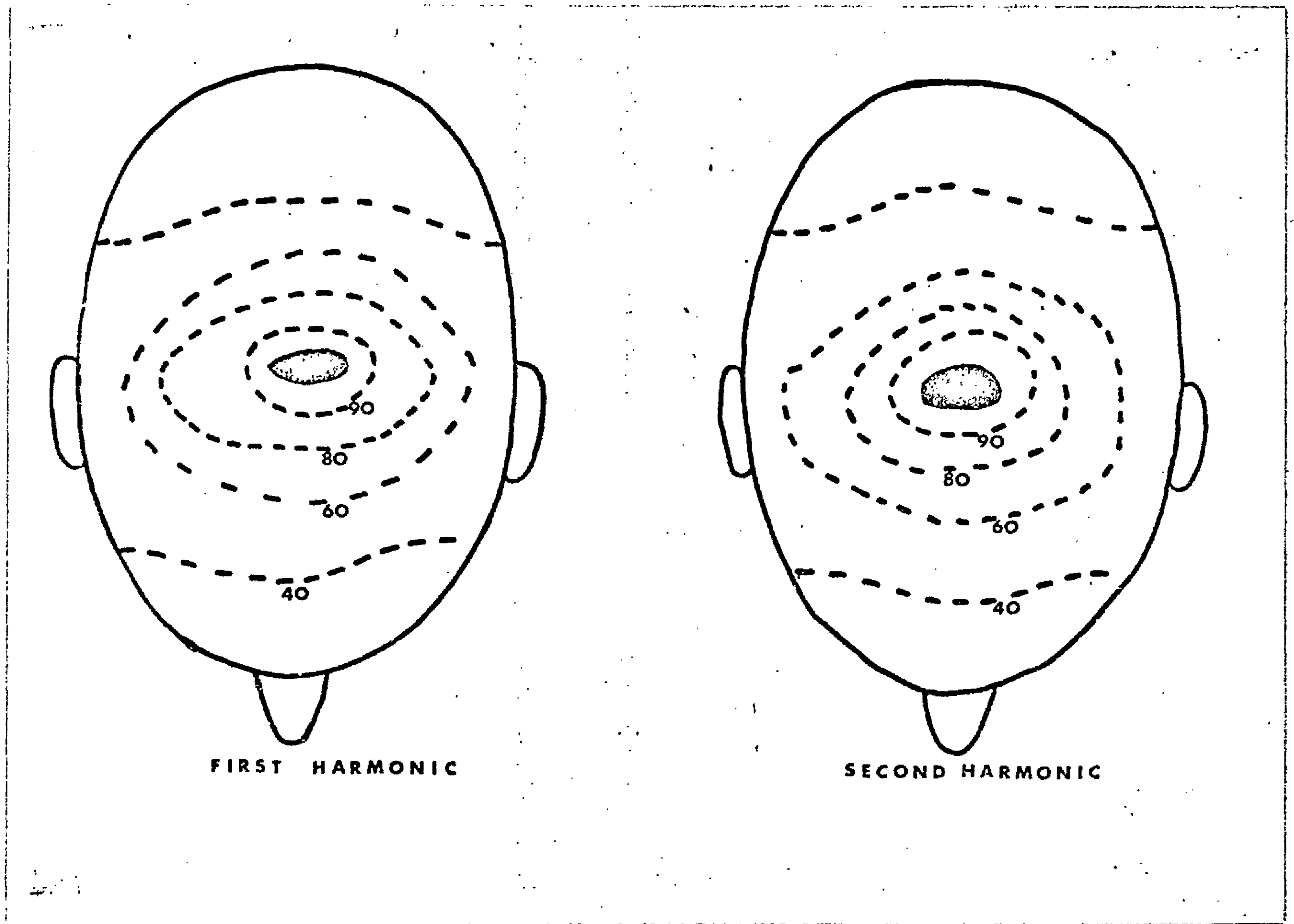


Figure 7.4 Spatial distribution of steady state responses to amplitude modulation.

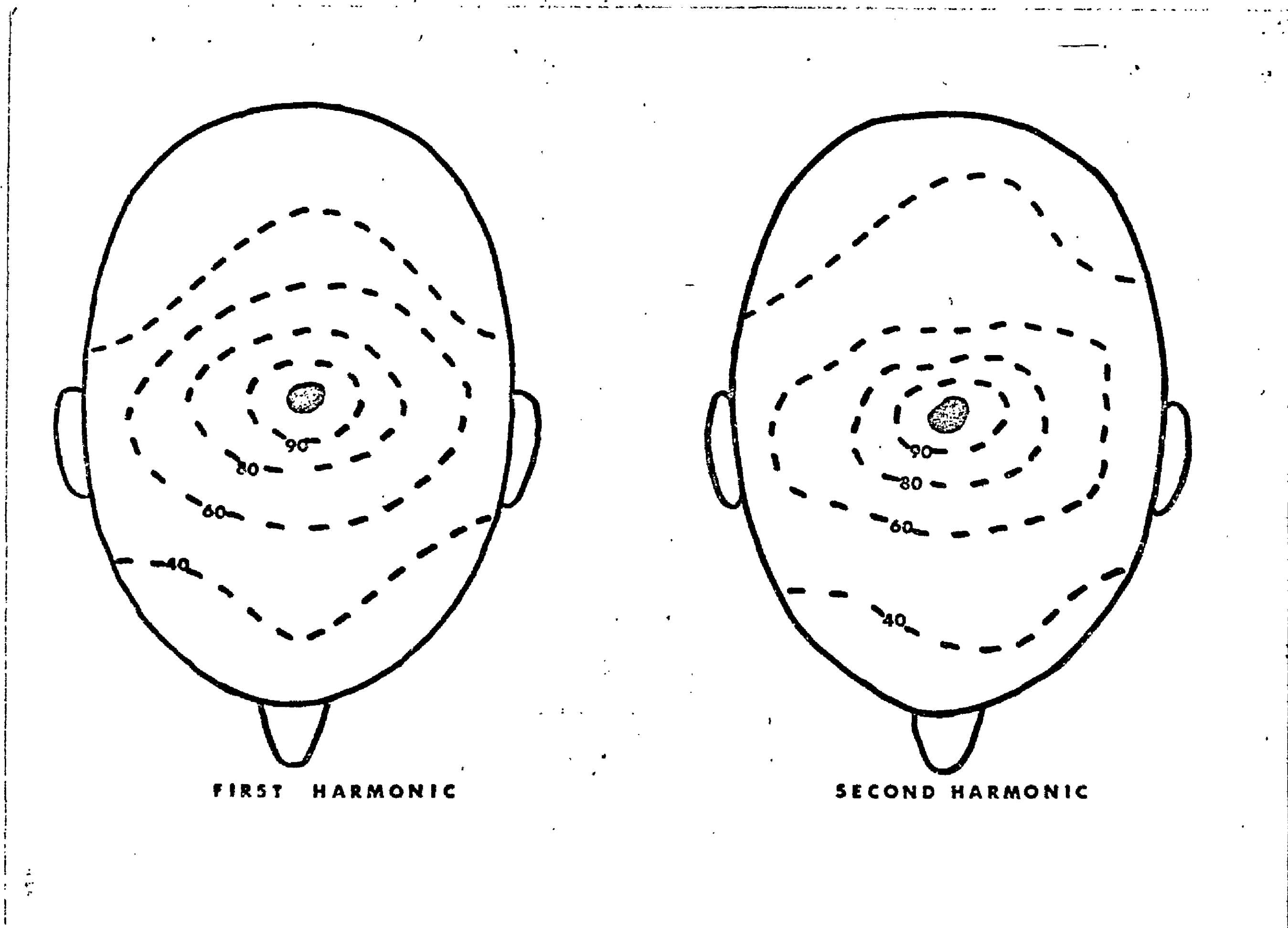
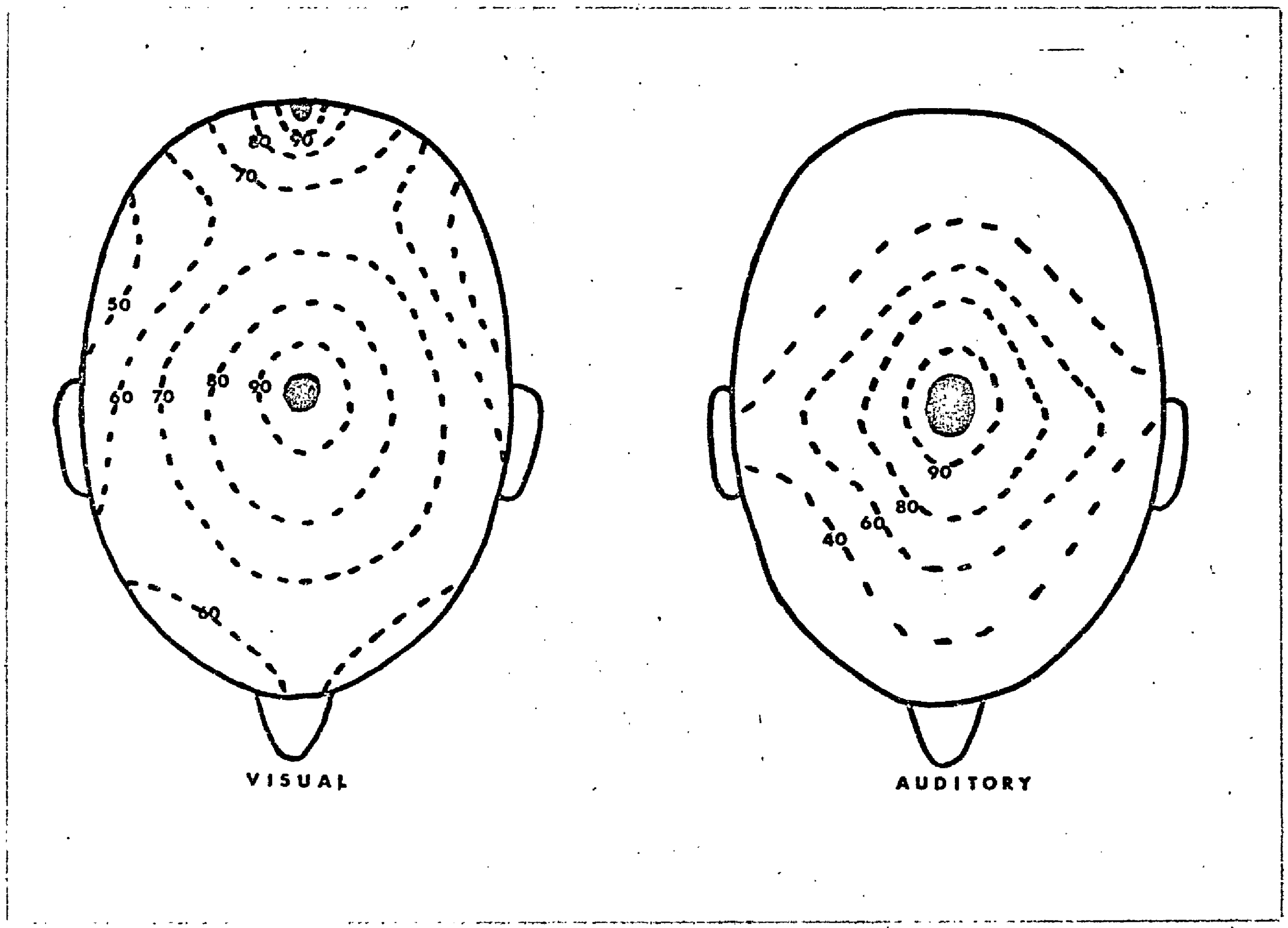


Figure 7.5 Spatial distribution of steady state responses to frequency modulation.



<u>Figure 7.6</u> Spatial distribution of transient responses to visual and auditory stimulation.

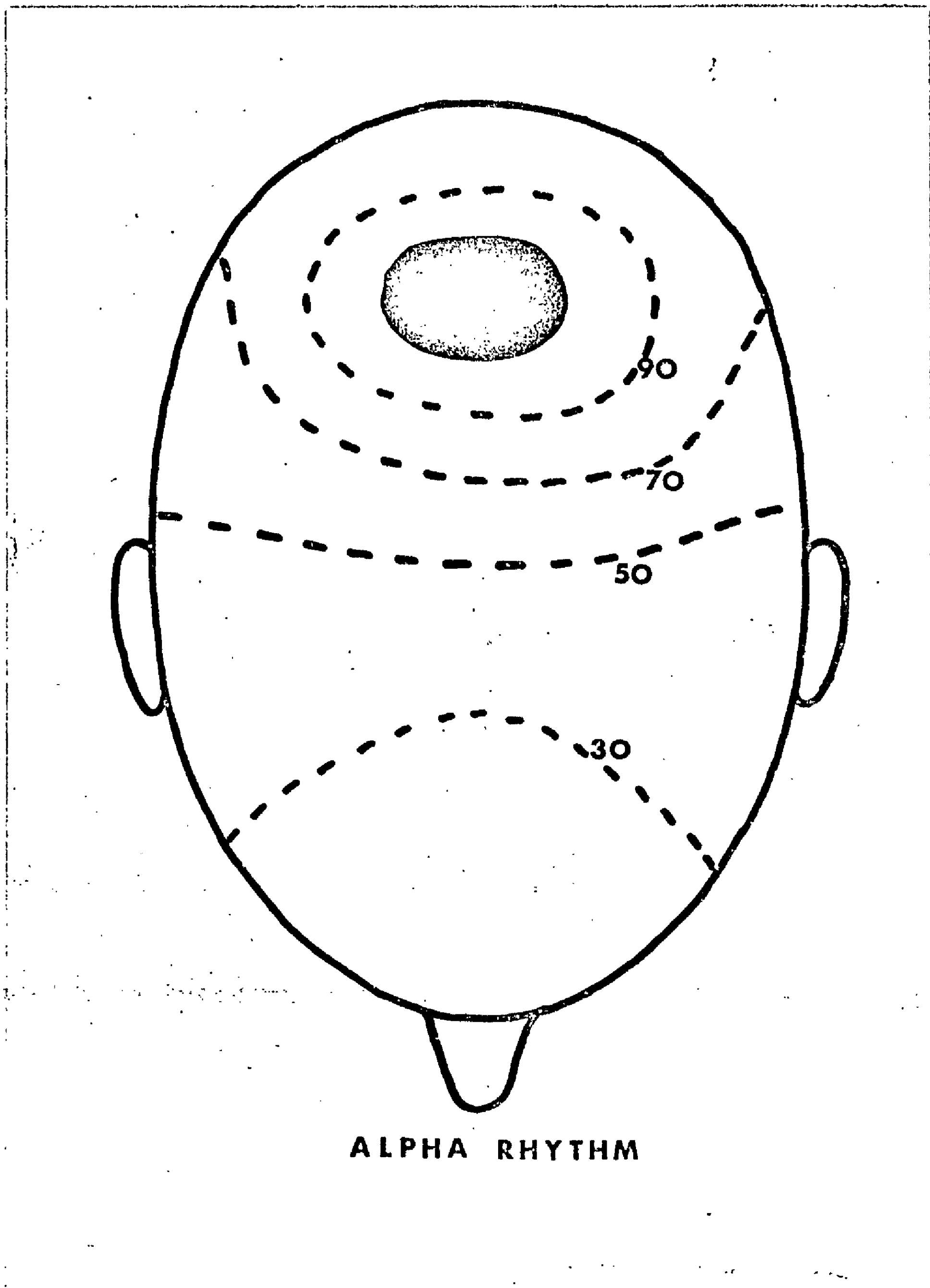


Figure 7.7 Spatial distribution of the alpha rhythm.

the frequency of alpha activity and the response region for steady state visual responses, while such a relationship does not occur for auditory stimulation. However, the distributions do indicate that the steady state auditory responses are not some form of alpha activity artefact.

7.5 Steady State Responses from Guinea Pigs

This section reports some steady state responses to amplitude and frequency modulated stimulation obtained from two guinea pigs. These results were obtained during work on a project concerning brain-stem responses to click stimulation and serve purely as an indication of how animal experiments may be used to gain an insight into steady state mechanisms.

Steady state responses were recorded from the scalp surface from both animals and the following results observed:-

(i) For amplitude modulated stimulation, responses are obtained from the awake animals at all modulation frequencies between 5 Hz and 15 Hz. The amplitude of the responses is approximately constant at about 3 uV, while the phase of the first harmonic appears to change linearly with modulation frequency. The computed time delays, τ, described in Section 2 of this Chapter are calculated to be 46 and 61 msecs for the two animals.

(ii) For frequency modulated stimulation in awake animals a similar behaviour is observed. The response amplitude is about 2 uV, and the time delays are 64 and 82 msecs.

(iii) When the animals are anaesthetised, no responses are detectable on the scalp surface.

(iv) During the course of the brain-stem experiments, the inferior colliculus is exposed, and the opportunity was taken of recording from this structure in one of the animals. Responses with an amplitude of about 5 uV are observed for both amplitude and frequency modulation at all modulation frequencies between 5 Hz and 15 Hz. Again the phase characteristics are linear with modulation frequency, giving a time delay of 41 msec for amplitude modulation, and 72 msec for frequency modulation.

This set of results is very similar to those obtained from dogs by Tielen et al (43), where responses were obtained at modulation frequencies up to 80 Hz. Both sets of experiments show clearly that the sharp dependence on modulation frequency, which occurs for amplitude modulated stimulation in humans, is not in evidence for dogs or guinea pigs. Thus the band pass filter, which is postulated to explain this dependence in human subjects, is likely to be a function of the individual human brain. Further experiments would be required to investigate properly the relationships between steady state responses from human and animal subjects.

7.6 Summary

Some similarities between steady state and transient responses have been established. The effect of carrier frequency on both types of response is found to be the same. The growth and decay of the two response types exhibit a similar form, with a plateau level followed by a gradual decay. Whilst the transient responses attain maximum amplitude almost immediately, the steady state responses require a period of entrainment before the maximum amplitude is achieved.

The transient and steady state responses have been related by converting the expression of steady state responses from amplitude and phase in the frequency domain, into delays in the time domain, which may be regarded as apparent latencies. The assumptions which have to be made to achieve this are rather severe, and greatly oversimplify the auditory system. Nevertheless, the latencies obtained are in the same range as the components of a transient evoked response.

Unlike steady state responses to visual stimulation, where the response region is related to the alpha frequency in the spontaneous EEG, it is not possible to predict the optimal frequency for amplitude modulation in auditory stimulation. There appears to be no correlation between the response envelope and the frequency characteristics of the spontaneous EEG.

Investigation of the spatial distribution of steady state responses to amplitude and frequency modulation has shown the similarity in the distributions for transient and steady state stimulation. The differences between auditory and visual responses are apparent, and the auditory potentials are found to have a very different distribution from the alpha activity.

A preliminary series of animal experiments has shown that the process, which causes the sharp dependence on modulation frequency for amplitude modulation, does not occur in guinea pigs.

CHAPTER 8

The Status of Steady State Responses in Audiology

8.1 Introduction

Previous chapters have discussed the relationships between steady state responses to both amplitude and frequency modulation, and the stimulus parameters required to elicit identifiable potentials. This chapter describes the advantages and the disadvantages of steady state responses as a method of auditory assessment, compared with the established procedure of averaged EEG audiometry, performed using transient tone burst stimulation.

A potential improvement in the analysis technique for steady state responses is discussed, a summary of the salient points regarding transient responses is given, and the strengths and weaknesses of steady state responses are put into perspective.

8.2 Improvements in Analysis Technique

The present method of analysis, whereby a single cycle average is constructed, converted into a periodic average, and then analysed in terms of its harmonic components is very time consuming. Experiments have shown that a figure of 1000 samples are required to form a good average, when the first 500 tokens are ignored. Thus 1500 cycles of modulation need to be presented to the subject. Thus, at a modulation frequency of 10 Hz, the stimulus is presented to the subject for 2½ minutes for a single determination. Whilst this is comparable to a single determination using transient stimulation, the time taken is considerable. Furthermore, the present procedure requires the presence of a PDP12 computer (or equivalent).

The experiments described in the preceding chapters have shown that the predominant harmonic component is the fundamental (first harmonic), and that the presence or absence of this first harmonic as a detection criterion, may be used to estimate behavioural threshold. Thus for purposes of clinical assessment, a full harmonic analysis may not be required and detection of the first harmonic alone may be sufficient.

The first harmonic (or other harmonics for that matter) may be derived by an analogue method (41) if the EEG signal and the modulating signal are available. This is described briefly below.

Let f (t) be the EEG signal and sin $2\pi Ft$ the modulating signal, where F is the modulation frequency. Electronic circuits (a combination of multipliers and integrators) are used to derive the signals:-

$$A = \int f(t) \sin 2\pi Ft dt$$

and

$$B = \int f(t) \cos 2\pi Ft dt$$

Then the amplitude S and phase $\emptyset$ of the first harmonic are given by:-

$$S = k \left[A^2 + B^2 \right]^{\frac{1}{2}} \quad \text{and } \emptyset = \tan^{-1} \left(\frac{A}{B}\right)$$

where k is a constant of calibration.

Thus an electric signal, S, may be obtained which represents the amplitude of the first harmonic component. The N^{th} harmonic may be obtained from the signals f(t) sin $2\pi(NF)t$ and f(t) cos $2\pi(NF)t$, but as the number of harmonics is increased, the number of components required becomes prohibitively large.

Work is under way to produce and test such a device; should this be successful, the analysis could be performed on-line and remove the requirement of an expensive digital computer. The computer analysis retains the advantage for research purposes where the amount of hardware to produce a full Fourier analysis would be greatly increased.

Analogue analysers have been used successfully in experiments on visual stimulation (41) and have displayed the advantage that the effects of a change in stimulus parameters may be noted almost immediately. Also, components with amplitudes in the range $0.1 \rightarrow 0.2$ uV have been detected, and this form of analysis may enhance the detectability of auditory steady state responses, as well as considerably reducing the time required for assessment.

8.3 Averaged EEG Responses to Transient Stimulation

A summary of the main properties of averaged EEG responses to transient stimulation is given below:-

(i) Responses may be detected reliably to within 10 dB of the behavioural threshold for adult subjects.

(ii) The response waveforms are not necessarily the same in young children as for adult subjects.

(iii) When sedation is used to make subject behaviour clinically acceptable, the response waveform may be altered.

(iv) In young and sedated children the reliability of response detection is considerably reduced.

(v) Unless complex analysis technique for machine scoring are used, response detection always requires an observer value judgement.

These properties are compared with the properties of steady state responses in the following sections, and the audiological implications are discussed.

8.4 Steady State Responses to Amplitude Modulation

The properties of these responses have been investigated in Chapters 3 and 4. The results are summarised below:-

(i) The region of response in the modulation frequency domain is sharply dependent on the modulation frequency. There always exists one or more response regions in the range 5 Hz to 15 Hz, but the position in the modulation frequency domain of the response regions exhibits a large degree of inter-subject variability. The responses are however, stable within each subject. It is not possible to predict the response region from the spectral content of the spontaneous EEG, and thus the optimal modulation frequency has to be determined for each individual. The maximum response amplitudes are in the range 1.5 uV to 3.5 uV as opposed to 10 uV for transient stimulation.

(ii) Other optimal parameters, such as modulation depth and number of samples in the average, are similar for all subjects.

(iii) Using the normal and plus-minus averages, a statistical detection criterion, which does not depend on observer performance, may be applied. Responses may be detected reliably to within 20 dB of behavioural threshold for adult subjects.

(iv) Response behaviour is similar to both adult and child subjects and always takes the form of a periodic signal at the fundamental frequency. The first harmonic component (fundamental) is always dominant.

(v) The response form is not affected by sedation. Responses are readibly detectable in sleep states 1 and 2 with a reliability similar to the awake state.

The above summary shows the attractions of assessment using steady state responses to amplitude modulated stimulation. The two unfavourable aspects are the reduced amplitude of the responses (leading to an over-estimation of hearing loss by about 20 dB) and the necessity to determine the optimal frequency of modulation for each subject.

8.5 Steady State Responses to Frequency Modulation

The properties of this class of response have been investigated in Chapters 5 and 6. The results are summarised below:-

(i) A single set of stimulus parameters is applicable to all subjects. Unlike the responses to amplitude modulation, a modulation frequency of 11 Hz elicits adequate responses in all normal hearing subjects. Thus no time need be spent in obtaining optimal conditions, and assessment may commence immediately. This may be important where co-operation time is limited.

(ii) Response amplitudes are in the range 1 uV to 2 uV, being smaller than responses to both amplitude modulation and transient stimulation.

(iii) The normal and plus-minus averages may be used to set up a signal detection criterion. Responses may be detected to within 40 dB of behavioural threshold.

(iv) The response behaviour does not change for children, and is not affected by sedation. The response threshold again overestimates the hearing loss by about 40 dB.

(v) The response thresholds and the behavioural thresholds exhibit a high degree of linear correlation and the linear regression relationship between the two sets of thresholds may be used to predict behavioural threshold from the steady state threshold.

Again the attractions of the above response behaviour are clear. The main drawback is the small amplitude of the responses, leading to an overestimation of hearing loss by about 40 dB. This makes assessment of hearing losses in the range 70 - 110 dB impossible.

Unless the analogue method of analysis proves productive, the drawback (which applies to all electrophysiological tests) that the procedure is very time consuming remains, and is liable to place an upper limit on the information obtainable in any one clinical session.

8.6 Conclusions and Suggestions for further study

While steady state responses to both amplitude and frequency modulated stimulation display many advantages over transient responses, the disadvantages in their application remain considerable. These merits and demerits have been summarised in the preceding sections, and it is clear that the steady state technique is not a replacement for averaged EEG audiometry to transient stimulation. However, where the results from the transient responses are equivocal (for the reasons given in Chapter 1), the steady state regime may prove to be of value. Long term tests under clinical conditions are required to assess its application fully, and these are now under way.

A possible improvement in the analysis technique for clinical purposes has already been described in this chapter. Other points which would bear investigation include the positions of the response regions in the modulation frequency domain for both amplitude modulated and frequency modulated stimulation. An explanation of the response behaviour for the two types of stimulation is required for the steady state, and this may prove possible through the use of animal experiments to construct models which describe the behaviour as a function of the experimental parameters.

APPENDIX I

APPENDIX I

Signal Averaging.

Let the input to the averaging device be denoted as f (t), and the required averaging time be T. The averager splits up each section of f (t) of length T (triggered by the stimulus) into M sections (1024 in the case of the Medelec device), of length Δt, so that f (t) is discretely described by:-

$$f_i\ (t) \quad \text{as} \quad i \rightarrow 1, M$$

The input waveform f (t) is assumed to be the sum of two independent waveforms, the signal waveform S (t) and a noise waveform n (t). The noise waveform is assumed to be a random stationary process with a mean E (n) and variance σ^2, and the signal waveform assumed to have zero variance (that is the signal is assumed to be exactly the same for each and every stimulus).

Then $$f_i = S_i + n_i$$

N samples of the input waveform f (t), are taken such that the signal component is time-locked to the start of each sample and the noise sections are uncorrelated.

The mean of these samples at the i^{th} point is given by:-

$$\bar{f}_i = \frac{1}{N} \sum_{k=1}^{N} f_{ik}$$

$$= \frac{1}{N} \sum_{k=1}^{N} (S_{ik} + n_{ik})$$

$$= \frac{1}{N} \sum_{k=1}^{N} S_{ik} + \frac{1}{N} \sum_{k=1}^{N} n_{ik}$$

$$= \bar{S}_i + \bar{n}_i = S_i + \bar{n}_i$$

since by assumption the S_i are identical. The expected value (statistical average) of the sample mean is then given by:-

$$E\,(f_i) = S_i + E\,(\bar{N}_i) = S_i + E\,(n)$$

If the mean value of the noise is assumed to be zero,

then

$$E\,(\bar{f}_i) = S_i$$

The variance of the sample mean at the i^{th} point may be obtained from the definition:

$$\sigma^2(\bar{f}_i) = \left| \frac{1}{N^2} \sum_{k=1}^{N} \sum_{p=1}^{N} E(f_{ik} f_{ip}) \right| - E^2(\bar{f}_i)$$

$$= \frac{1}{N^2} \sum_{k=1}^{N} \sum_{p=1}^{N} \left[E(S_{ik} S_{ip}) + E(n_{ik} n_{ip}) \right] - S_i^2$$

The samples of n(t) have been assumed to be uncorrelated.

Therefore:-

$$E\,(n_{ik}\, n_{ip}) = 0 \quad \text{for } k \neq p$$

And so

$$\sigma^2(\bar{f}_i) = S_i^2 + \frac{1}{N} E(n_i^2) - S_i^2$$

$$= \frac{1}{N} \sigma^2(n_i)$$

$$= \frac{1}{N} \sigma^2(n)$$

Thus after N samples have been taken, the expected value of the sample mean is equal to the amplitude of the signal component, and the variance of the sample mean is $\sigma^2(n)/N$. So the expected values for one sample and for N samples are both S_i. but the variance about the mean is $\sigma^2(n)$ for one sample and $\sigma^2(n)/N$ for N samples.

The signal-to-noise ratio is defined as the expected value of the signal divided by the standard deviation of the noise, and is then $S_iK(n)$ for one sample and $S_iK(n)$ N for the average of N samples. Thus, subject to the assumptions above, (especially that the noise samples are uncorrelated) performing an average over N samples improves the signal-to-noise ratio by a factor of $\sqrt{N}$.

The above analysis considers the extreme case of completely uncorrelated noise. Averaging can still give some enhancement of signal-to-noise when this assumption is not valid, but where a correlation does exist between the noise samples the improvement may be less than the factor $\sqrt{N}$.

The assumption that both the noise and the signal are stationary processes (that is a description of either signal which is valid at any instant is equally valid at some later time) may not hold, and this again may cause the signal-to-noise enhancement obtained in practice by summing a large number (N) of EEG samples to fall well below the predicted value of N. Examples of situations where serious departures from stationarity occur are:- (a) when N sweeps are averaged during experimental procedures which are so boring that the subject grows fatigued so that the evoked potential changes in amplitude or phase (or becomes increasingly variable) and (b) averages of N sweeps during which the subject becomes so bored and sleepy that the alpha activity becomes progressively more obtrusive.

The practical outcome of these considerations is that, even after enhancement by signal averaging, the contamination of the signal by noise can often not be neglected.

APPENDIX II

APPENDIX II

Fourier Analysis

Let f (t) be a periodic function of period 2π, which satisfies Dirichlet's conditions:

(i). That the integral $\int_{-\pi}^{\pi} |f(t)|\, dt$ is finite.

and..

(ii) f (t) is piecewise continuous.

Then f (t) may be represented as:-

$$f(t) = a_0 + \sum_{n=1}^{\infty} (a_n \cos nt + b_n \sin nt)$$

where $a_0 = 1/_\pi \int_{-\pi}^{\pi} f(t)\, dt$

$$a_n = 1/_\pi \int_{-\pi}^{\pi} f(t) \cos nt\, dt$$

and $b_n = 1/_\pi \int_{-\pi}^{\pi} f(t) \sin nt\, dt$

Functions having period other than 2π may be accommodated by setting $t' = \frac{2\pi}{T} . t$ where T is the period.

Thus any periodic function may be described by a sum of series of sines and cosines

Now...

$$a_n \cos nt + b_n \sin nt = (a_n^2 + b_n^2)^{1/2} \left[\frac{a_n \cos nt}{(a_n^2 + b_n^2)} + \frac{b_n \sin nt}{(a_n^2 + b_n^2)} \right]$$

$$= A_n \cos (nt - \emptyset n)$$

where $\tan \emptyset = b_n/_{a_n}$ and $A_n = (a_n^2 + b_n^2)^{1/2}$

Thus...

$$f\ (t) = 1/2\ a_0 + \sum_{n=1}^{\infty} A_n \cos(nt - \emptyset_n)$$

Thus f (t) may be described as a series of cosines, (or, of course, sines) with amplitude A_n and phase $\emptyset_n$.

A complex form of the analyses may be derived (46), where...

$$f\ (t) = \sum_{n=\infty}^{\infty} C_n\ e^{int}$$

$$C_n = 1/2\pi \int_{\infty}^{\infty} f\ (t)\ e^{-int} dt$$

$$= 1/2\ (a_n - ib_n)$$

Thus in complex form, the amplitude of each harmonic is given by 2 C_n and the phase of each component by $\tan^{-1} \dfrac{I_m\ (C_n)}{R_e\ (C_n)}$

The analysis programme used (FFTDEAE) was in fact a more generalised Fourier transform which could be used for non-periodic wave forms. It functions however perfectly adequately for harmonic analysis of a periodic signal, outputting the complex of Fourier coefficient C_n at each multiple of the fundamental frequency.

Thus from each C_n the amplitude and phase of each harmonic of the input wave form may be obtained.

APPENDIX III

APPENDIX III

The Plus - Minus Average

The plus-minus average is a variation on the process of signal averaging described in Appendix I, with the input to the averager alternately added and subtracted in the device, instead of constantly added. The assumptions on the input wave form f (t) are the same as for the normal average and the plus-minus mean of the N samples at the i^{th} point is given by:-

$$\bar{f}_i \ (\pm) = \frac{1}{N} \sum_{k=1}^{N} k^{-1} \ f_{ik}$$

$$= \frac{1}{N} \sum_{k=1}^{N} k^{-1} (S_{ik} + N_{ik})$$

$$= \frac{1}{N} \sum_{k=1}^{N} k^{-1} S_{ik} + \frac{1}{N} \sum_{k=1}^{N} k^{-1} N_{ik}$$

Now the signal wave form S (t) is assumed to be the same for each and every stimulus.

So...

$$\frac{1}{N} \sum_{k=1}^{N} k^{-1} S_{ik} = \frac{1}{N} (S_i - S_i + S_i \ldots.) = 0 \text{ if N is even.}$$

If n (t) is assumed to be a random stationary process....

$$\sum_{k=1}^{N} k^{-1} n_{ik} = \sum_{k=1}^{N} n_{ik}$$

Therefore..

$$\bar{f}_i \ (\pm) = \bar{n}_i$$

That is the plus-minus average consists solely of residual EEG activity. An analysis similar to Appendix I achieves the results that $\sigma^2(\bar{f}_i) = \frac{1}{N}\sigma^2(n)$ if the noise (that is the EEG) is a purely random process. Thus the plus-minus average is a measure of the residual noise in the normal average. The simple derivation assuming as it does that the signal (or response) wave form is invariant and that the noise (or EEG) wave form is random and stationary, makes this approach only an approximation, in the same way that the improvement in signal to noise of N in the normal average is an approximation. The generation of the plus-minus average is easily achieved by the averaging programme in the PDP 12 computer. It is advantageous in a clinical situation however, to have both the averages available at the time of recording. Consequently an electronic circuit was devised to change the polarity of the EEG input to the Medelec averager on each alternate sample sweep. This circuit is shown in Fig. A.1. The trigger is derived from the Medelec, which is itself triggered by the modulation signal, and the EEG is then switched between an inverting and non-inverting operational amplifier. The dual channel Medelec system then displays both the normal average (containing the response plus residual EEG activity) and the plus-minus average (containing residual EEG activity).

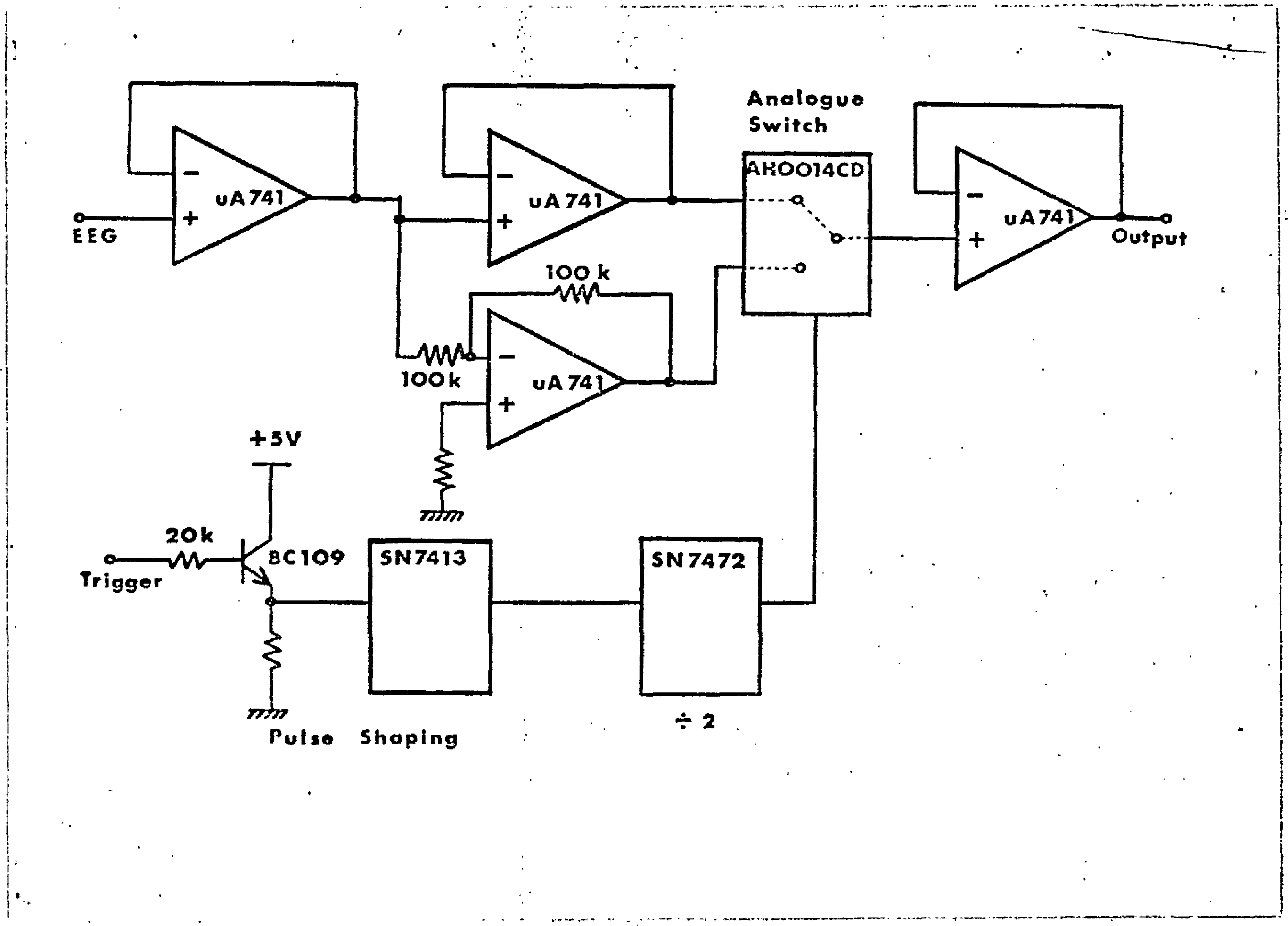


Figure A.1 Circuit to generage the plus-minus EEG signal.

REFERENCES

REFERENCES

(1) KATZ, J. (1970). Audiologic diagnosis: cochlea to cortex. Menorah med. J. 1:25-38.

(2) DAVIS, H. and SILVERMAN, S.R. (1960). Hearing and deafness. (Holt, Rinehart and Winston, London 1960).

(3) BUNCH, C.C. (1941). The development of the audiometer. Laryngoscope 51:1100-1118.

(4) JERGER, J. (1960). Bekesy audiometry in the analysis of auditory disorders. J.Speech and Hearing Res. 3:275-287.

(5) WEDENBERG, E. (1956). Audiometry tests on newborn infants. Acta oto-laryng. Stockh. 46:446-461.

(6) DOWNS, M.P. and STERRITT, G.M. (1967). A guide to newborn and infant screening programs. Arch. Oto-laryng. 85:37-44.

(7) ANDERSON, H. (1967). Acoustic intra-aural reflexes in clinical diagnoses. (Ka - Ve Tryck Stockholm 1967).

(8) NIEMEYER, W. and SESTERHENN, G. (1974). Calculating the hearing threshold from the stapedius reflex threshold for different sound stimuli. Audiol. 13:421-427.

(9) ARAN, J.M. (1971). The electrocochleogram. Recent results in children and in some pathalogical cases. Arch. H.N.O. 198:128-143.

(10) YOSHIE, N. (1973). Diagnostic significance of the electrocochleogram in clinical audiometry. Audiology 12:504-539.

(11) DAVIS, H. (1973). Classes of auditory evoked responses. Audiology 12:464-469.

(12) DAVIS, H. (1965). Slow cortical responses evoked by acoustic stimuli. Acta oto-laryng. Stockh. 59:179-185.

(13) ZERLIN, S. and NAUTON, R.F. (1974). Early and late averaged EEG responses at low sensation levels. Audiology 13:366-378.

(14) DAVIS, H., BOWERS, C. and HIRSH, S.K. (1968). Relations of the human vertex potential to acoustic input: loudness and masking. J.Acoust.Soc.Amer. 43:431-438.

(15) DAVIS, H. and ZERLIN, S. (1966). Acoustic relations of the human vertex potential. J.Acoust.Soc.Amer. 39:109-116.

(16) BUTLER, R.A., KEIDEL, W.D. and SPRENG, M. (1969). An investigation of the human cortical evoked potential under conditions of monaural and binaural stimulation. Acta oto-laryng. Stockh. 68:317-326.

(17) DAVIS, H. (1966). Validation of evoked response audiometry in deaf children. Int.Audiol. 5:77-81.

(18) RAPIN, I. and GRAZIANI, L.J. (1967). Auditory evoked responses in normal, brain damaged and deaf infants. Neurology 17: 881-894.

(19) BEAGLEY, H.A. and KNIGHT, J.J. (1967). The auditory evoked cortical response as an index of hearing in practical audiometry. J.Laryng.81:347-351.

(20) BEAGLEY, H.A. (1973). The rate of electrophysiological tests in the diagnosis of non-organic hearing loss. Audiology 12:470-480.

(21) SUZUKI, T., YAMAMOTO, K., TAGUCHI, K. and SCKABE, N. (1976). Reliability and validity of late vertex evoked response audiometry. Audiology 15:357-369.

(22) BEAGLEY, H.A. and KELLOGG, S.E. (1969). A comparison of evoked response and subjective audiometry thresholds. Int.Audiol. 8:345-353.

(23) BEAGLEY, H.A. and KELLOGG, S.E. (1970). A survey of hearing by evoked response audiometry in a group of normally hearing schoolchildren. J.Laryng. otol. 84:481-493.

(24) DAVIS, H. and ONISHI, S. (1969). Maturation of auditory evoked potentials. Int.Audiol. 8:24-33.

(25) KEATING, L.W. and RUHM, H.B. (1971). Some observations on the effect of attention to stimuli on the amplitude of the acoustically evoked response. Int.Audiol. 10:177-184.

(26) MAST, T.E. and WATSON, C.S. (1968). Attention and auditory evoked responses to low detectability signals. Percept. Psychophys. 4:237-248.

(27) HERZ, A., FRALING, F., NIEDNER, J. and FABER, G. (1967). Pharmacologically induced alterations of cortical and sub-cortical evoked potentials compared with physiological changes during the wake sleep cycle in cats. Electroenceph. clin. Neurophysiol. suppl. 26:164-175.

(28) MADELL, J. (1974). Influence of stimulus level and sleep stage on the early components of the averaged EEG response to clicks in all-night sleep. J. Speech and Hearing Res. 14:23-32.

(29) KARNEHL, T. and BENNING, C.D. (1971). Relationship between amplitude, latency and sound pressure level in the ERA (with and without sedation). Arch. klin. exp. Ohr-Nas-KehlkHeilk. 198:9-73.

(30) STANGE, G. (1971). The effect of sedative agents and psychotropic drugs on acoustically evoked responses. Arch.klin.exp. Ohr-Nas-KehlkHeilk. 201:294-308.

(31) WILLIAMS, H.L., MORLOCK, H.C., MORLOCK, J.W. and LUBIN, A. (1964). Auditory evoked responses and the EEG stages of sleep; in KATZMAN, Sensory evoked potentials in man. Ann.N.Y.Acad.Sci. 112:160-171.

(32) BIESALSKI, P. LEITNER, H. and MULLER-GERHARD, N. (1976). Relations between electric response audiometry and psychodiagnostic examinations in hearing impaired children. Audiol. 15:376-383.

(33) SHEPHERD, D.C., WEVER, O.R. and McCARREN, K. (1972). Techniques to reduce the negative effects of high voltage electrical artefacts during averaged EEG audiometry. J.Speech and Hearing Res. 15:142-155.

(34) ROSE, D.E., KEATING, L.W., HEDGECOCK, L.D., SCHEURS, K.K. and MILLER, K.E. (1971). Aspects of acoustically evoked potentials. Inter-judge and intra-judge reliability. Arch. Otol. 94:347-350.

(35) SCHIMMEL, H., RAPIN, I. and COHEN, M.M. (1974). Improving evoked response audiometry with special reference to machine scoring. Audiol. 13:33-65.

(36) DONCHIN, E. and LINDSLEY, S. (1969). Average evoked potentials Methods, results, evaluation. NASA Conference Report 1-43.

(37) JERGER, J. and JERGER, S. (1970). Evoked response to intensity and frequency change. Arch. Oto-laryng. 91:433-436.

(38) FUNASAKA, S., KODERAK, K. and ABE, H. (1974). The auditory stimuli to evoke a clear average response at behavioural threshold. Audiology 13:162-172.

(39) LENHARDT, M.L. (1971). Effect of frequency modulation on the auditory evoked response. Audiology 10:18-22.

(40) SPOOR, A., TIMMER, F. and ODENTHALL, D.W. (1969). The evoked auditory response to intensity modulated and frequency modulated tones and tone bursts. Int.Audiol. 8P 410-415.

(41) REAGAN, D. (1972). Evoked potentials in psychology, sensory physiology and clinical medicine. (Chapman and Hall, London 1972).

(42) REAGAN, D. Evoked potentials and psychophysical correlates of changes in stimulus, colour and intensity. Vision Res. 10:163-178.

(43) TIELEN, A. et al (1969). Evoked responses to sinusoidally modulated sound in unanaesthetised dogs. Electroenceph.clin.Neurophysiol. 26:381-293.

(44) RODENBURG, M. et al (1972). Analysis of evoked responses in man elicited by sinusoidally modulated noise. Audiology 11:283-293.

(45) SCHIMMEL, H. (1967). The (±) Reference:- Accuracy of estimated mean components in average response studies. Science 157:92-94.

(46) STUART, R.D. (1961). An introduction to Fourier analysis. John Wiley and Son, London.

(47) RECHTSCHAFFEN, A. and KALES, A. (1968). A manual of standardised terminology, techniques and scoring system for sleep stages. National Inst. of Health Publ. No. 204 (US Govt. printing office, Washington, 1968).

(48) FROST, J. (1970). An automatic sleep analyser. Electroenceph.clin. Neurophysiol. 29:88-92.

(49) WANTANABE, T. and OHGUSH, K. (1968). A frequency sensitive auditory neurone. Proc.Japan.Acad. 44:968-973.

(50) SPEKREIJSE, H. (1966). Analysis of EEG responses in man. Junk Publishers, The Hague, The Netherlands.

(51) JASPER, H.H. (1958). The ten-twenty electrode system of the International Federation. Electroenceph.clin.Neurophysiol. 10:371-375.

(52) VAUGHN, H.G. and RITTER, W. (1970). The sources of auditory evoked responses recorded from the human scalp. Electroenceph.clin. Neurophysiol. 28, 360-367.

(53) HILL, J.D.N. and PARR, G. (1950). Electroencephalography. MacDonald and Co., London.