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PERCEPTUAL AND ELECTROPHYSIOLOGICAL
MASKING OF THE AUDITORY BRAINSTEM RESPONSE

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ABSTRACT

Effective masking levels of the auditory brainstem response (ABR) to tonepips were established on 10 normal-hearing subjects at 500, 1000, 2000 and 4000 Hz, using white noise. Effective masking levels of perceptual responses to the same stimuli were also established, for both presentation of single (1/second) and repeated (41.7/second) tonepips. Perceptual masking levels for repeated tonepips were significantly higher than levels for single tonepips, indicating temporal summation effects. Levels which effectively masked the ABR did not differ significantly from perceptual masking levels at either presentation rate. A signal-to-noise ratio of -5 to -10 dB was found to provide effective masking for all conditions. For the stimulus and recording parameters in the present study, a behavioural method of determining effective masking levels is considered appropriate. Behavioural thresholds determined for single tonepips were higher than thresholds for repeated tonepips, demonstrating dependence of nHL behavioural references for ABR thresholds on stimulus repetition rate. Effective masking levels determined in the present study may be applied to the use of tonepip ABRs to provide an objective frequency-specific measure of hearing in infants.

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INTRODUCTION

BACKGROUND

In 1971 Jewett and Williston described a procedure to record auditory evoked far-field electrical potentials from the human scalp. This recorded response, known as the auditory brainstem response (ABR), is the result of electrical responses in the nervous system to auditory stimuli. The cells being activated have overlapping field potentials which are able to be recorded from a distance via electrodes placed at various positions on the head and neck. Because of these overlapping fields, the evoked potentials are largest when the cells are activated synchronously, and are most easily evoked by the onset of a stimulus (Elberling, 1976). Even if a prolonged stimulus is used, only the onset evokes the response. For this reason auditory evoked potentials are best measured by using brief auditory stimuli such as clicks or brief tones.

This ability to evoke the ABR in response to clicks has been used extensively in clinical applications as a reliable and objective assessment of auditory function (Coates, 1978; Galambos and Hecox, 1978). The typical ABR is characterized by a series of peaks and valleys occurring within the first 10 ms (milliseconds) after stimulus onset. As many as seven or eight peaks may be seen

although the first five are the most stable. These "waves" are known as the early latency responses and are believed to be generated from various nuclei in the ascending auditory pathway. Although the neural generators of each peak have not been established with certainty, the most simplistic hypothesis assigns the origin of the first peak (wave I) to the auditory nerve, the second to the cochlear nucleus, the third to the superior olivary complex, the fourth to the lateral lemniscus and the fifth to the inferior colliculus (Janetta, Moller and Moller, 1981). Responses at longer latencies have also been recorded, which are believed to be of cortical origin (Arslan, Prosser and Michelini, 1984). These are termed the middle latency response (10 - 300 ms) and the late response (300+ ms). While research has investigated the clinical utility of these responses, it is the early response (ABR) that has proved most useful to date (Jacobson and Hyde, 1985).

ABR interpretation is generally based on latencies (in milliseconds) of individual waveforms, interpeak latencies, peak amplitude and overall waveform morphology. Figure 1 shows an example of a click-evoked ABR. Alterations in one or more of these parameters are used for diagnostic decision making in a range of audiological and otoneurological applications, for example, the diagnosis of space-occupying lesions on the VIII (auditory) nerve or at the level of the brainstem (Selters and Brackman, 1977). Wave V has been found to be particularly robust and

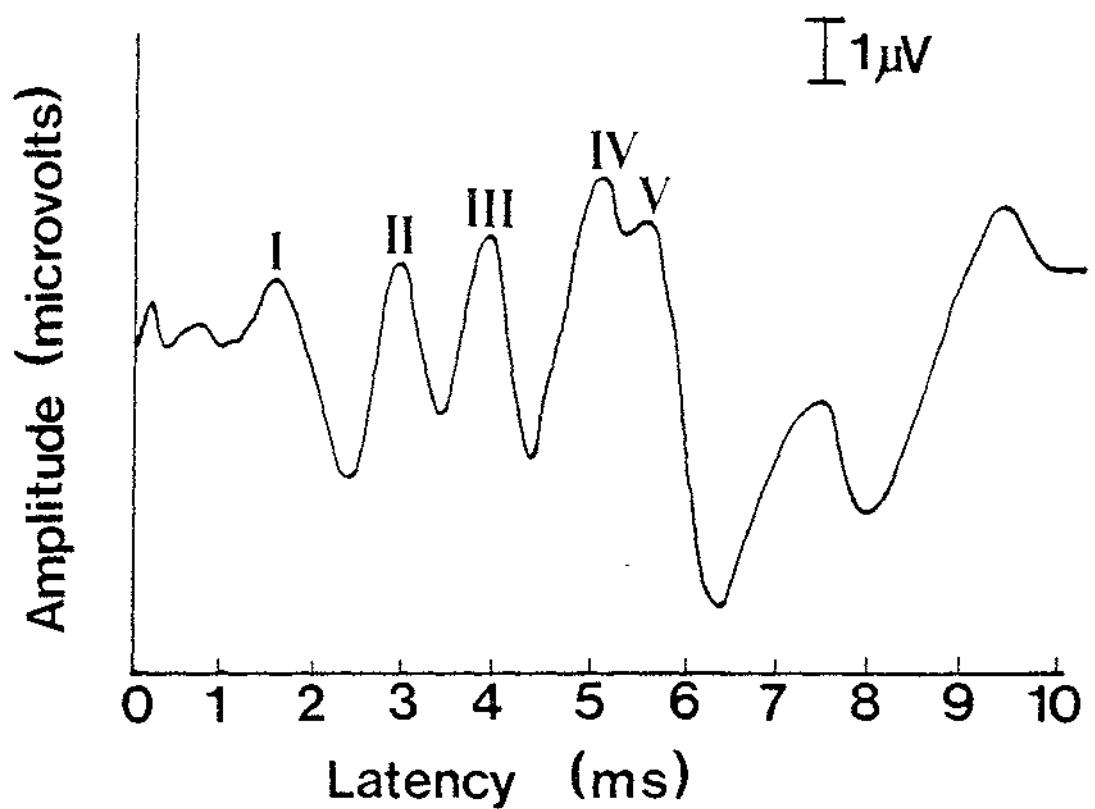


Figure 1. Example of a normal click ABR
for an adult male. (from Schwartz and
Berry, 1985, p.66).

reliable under varying measurement conditions and as such has received the most widespread clinical attention in differential diagnosis of otoneurologic disorders and estimation of hearing sensitivity (Schwartz and Berry, 1985).

The use of the ABR as an objective means of measuring hearing sensitivity has been especially important for assessing difficult-to-test patients and neonates/infants who are otherwise unable to give reliable behavioural responses to auditory stimuli (Folsom, 1985; Hyde, 1985; Jacobson, 1985). In the case of testing infants, attempts to measure hearing by behavioural paediatric tests (which require a subjective response from the infant) are limited by the response repertoire available to human infants, particularly at less than six months of age (Folsom, 1985). During these early months of life, the interpretation of behavioural responses is influenced by variables such as infant activity state and dependence on stimulus novelty. As a result, a wide range of minimum response levels has been observed in normal infants, and hearing thresholds are usually elevated compared to normal-hearing adult thresholds (Wilson and Thompson, 1983). The ABR, however, has been shown to provide an objective and accurate assessment of high-frequency hearing in infants (Hecox and Galambos, 1974).

While a lot of ABR normative data pertaining to infants have been collected, they are largely specific to the laboratory or clinical setting in which the studies have been done (Jacobson, 1985; Durieux-Smith et al., 1985). The susceptibility of the ABR to changes in clinical procedure and testing parameters requires test results to be compared to clinic or equipment-specific norms. The present study was designed to establish further normative data on the ABR with a view toward providing more efficient and informative methods of assessing hearing in infants.

FREQUENCY SPECIFICITY

To validate the use of the ABR as a measure of hearing sensitivity, many studies have attempted to match evoked potential thresholds (the lowest stimulus intensities that result in a repeatable ABR) to hearing thresholds (Sohmer and Kinarti, 1984; McGee and Clemis, 1980; Hayes and Jerger, 1982). Most studies have indicated that the click ABR threshold is most comparable with hearing in the frequency region 2 - 4 KHz, but yields little information about the lower frequencies (Coates and Martin, 1977). A major difficulty in attempting to measure hearing sensitivity across the frequency range by using ABR audiometry is the lack of frequency specificity available when using brief broad spectrum acoustic stimuli such as clicks.

This lack of frequency specificity results from two factors, namely, the spectral characteristics of brief stimuli, and cochlear mechanics.

A click, which is produced by passing a brief (usually 100 microseconds) square wave through an earphone, has a broad frequency spectrum. Brief tones, while having some concentration of energy at the nominal frequency of the tone, also have sidebands of energy at adjacent frequencies. This spread of energy, known as "spectral splatter", means that the ABR to these stimuli may be evoked by many of the frequencies in the spectrum as well as the nominal frequency (Durrant, 1983). Typical spectra for click and tonepip stimuli are shown in Figures 2 and 3.

Frequency analysis in the cochlea is thought to occur by a number of mechanisms. Bekesy (1960) has demonstrated the mechanics of the cochlear travelling wave which moves from the base to the apex of the basilar membrane.

High-frequency stimulation causes maximum vibration basally while low-frequency stimulation causes maximum vibration apically with some additional basal stimulation. The velocity of the travelling wave decreases such that the extent of basilar membrane activated by a particular frequency increases as the wave moves from base to apex. Thus the travelling wave results in a place coding for frequency on the basilar membrane. One means of discriminating frequencies (distinguishing two tones on the

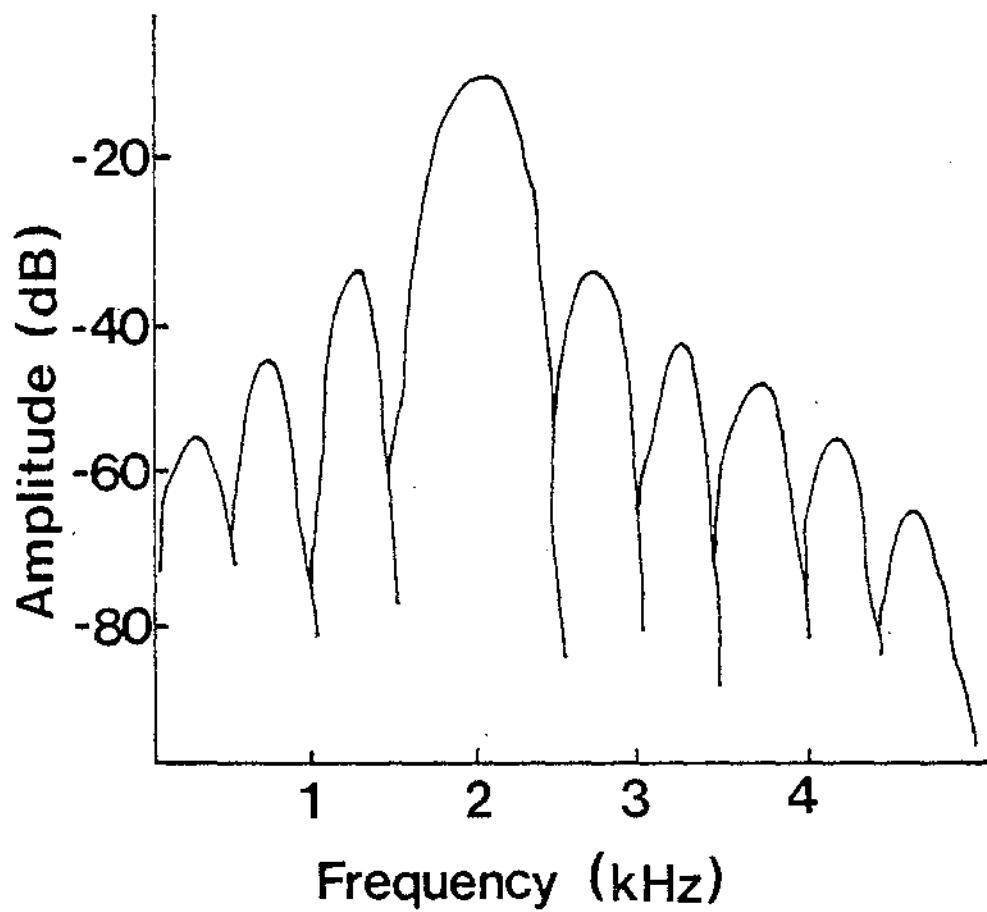


Figure 2. Electrical amplitude spectrum for a 2000 Hz tone pip using a 2 ms linear gating function.
(from Gorga, Abbas and Worthington 1985, p. 59).

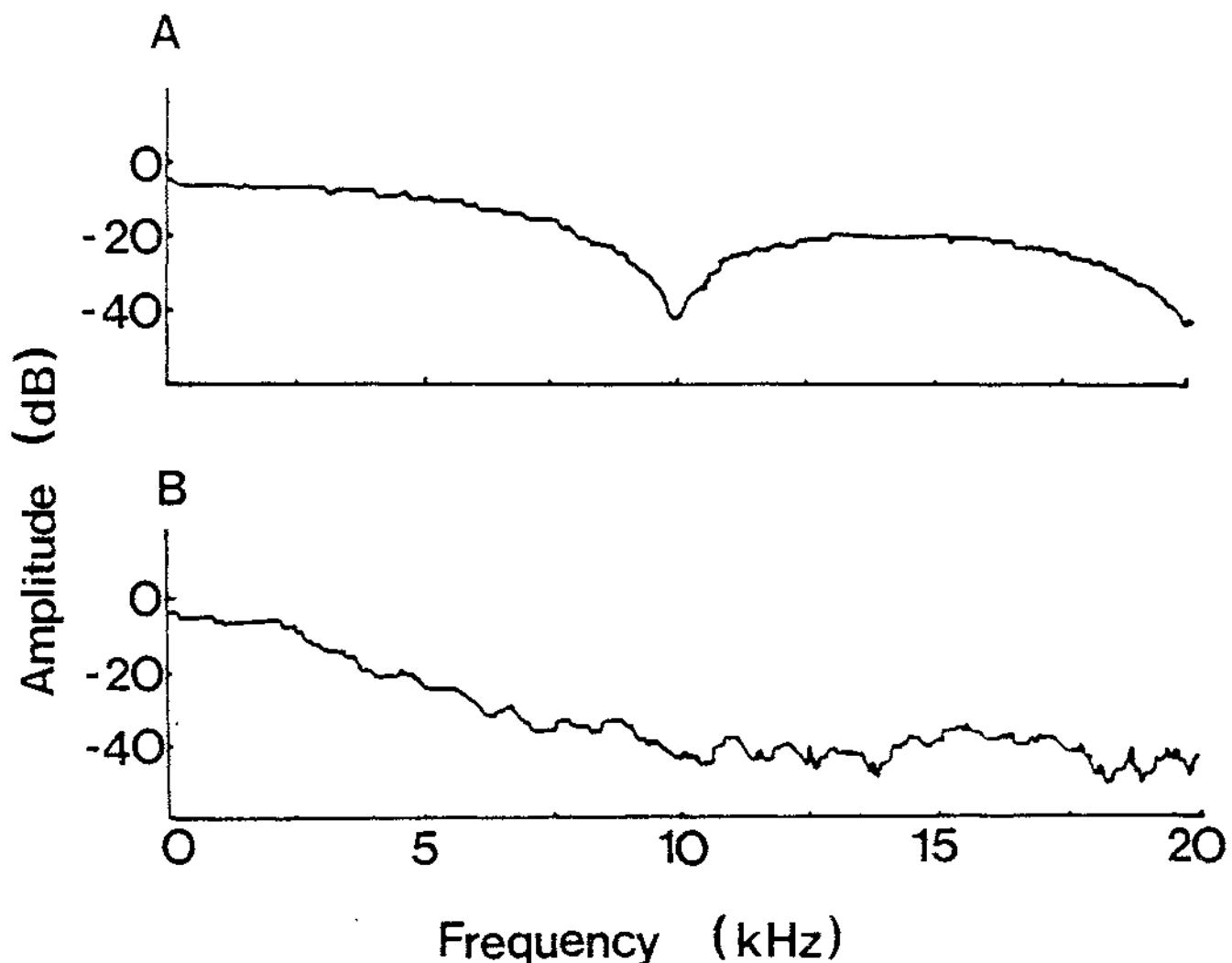


Figure 3. Typical amplitude spectrum for a 100 microsecond click measured (A) electrically and (B) acoustically.
(From Gorga, Abbas and Worthington, 1985, p.56).

basis of frequency when they are separated in time) is thought to result from the detection of shifts in the place of maximum excitation in the cochlea. This is known as "place theory" (Zwicker, 1970). The mechanical frequency resolving power of the basilar membrane however, cannot account entirely for known frequency discrimination ability in humans (Nordmark, 1970). A second filter mechanism has also been postulated as a means of "fine tuning" the neural response to make it more frequency specific (Gorga and Worthington, 1983).

Temporal theories have also been advocated, in which discrimination is based on the time intervals between the neural firings of different tones. This is based on the fact that firing of the auditory nerve is phase-locked to the stimulus waveform up to 5 KHz (Pickles, 1982). Thus, phase locking of neuronal discharges to the periodicity of the auditory stimulus is thought to be a further means for providing frequency information.

When using brief stimuli such as clicks, spectral splatter can cause widespread stimulation along the basilar membrane. The fact that the most recognizable components of the click-ABR response derive from the 2 - 4 KHz region of the cochlea is because high-frequency regions of the cochlea are located close together in an area of the basilar membrane where the travelling wave has relatively high velocity, resulting in a more synchronized discharge and a higher amplitude response (Stapells et al., 1985).

Transducer (earphone) effects on the stimulus spectrum may also contribute to this largely high-frequency response. Most earphones used for audiological testing display two primary resonant peaks between 3000 and 6000 Hz which can interact with the stimulus (Schwartz and Berry, 1985).

Thus, while an ABR to click stimuli gives a general idea of auditory sensitivity at higher frequencies, losses restricted to the low frequencies may not be detected. For example, Picton, Ouelette, Hamel, and Durieux-Smith (1979) have recorded normal click-evoked ABRs from ears having significant low- and mid-frequency losses (as determined by standard audiometric procedures).

A method that yields information at specific frequencies would therefore provide a more accurate measure of hearing sensitivity across the range of speech frequencies. Such frequency-specific information is necessary for optimal hearing aid selection. For example, most hearing aid selection procedures aim to amplify the speech frequencies to a comfortable listening level in order to maximize speech intelligibility (Hodgson, 1986). This involves the selection of a required amount of amplification at specific frequencies based on accurate assessment of hearing thresholds at those frequencies.

One means to improve frequency specificity is to use stimuli such as bandpass filtered clicks or tonepips, which have relatively narrow spectra yet still have onset

times sufficiently short to generate a synchronous neural response. When using these brief stimuli, the resultant ABR generally shows only one clear vertex-positive wave occurring within 20 ms after the onset of the stimulus (Stapells and Picton, 1981).

Brief high-frequency tones have been found to elicit brainstem responses which are similar to those evoked by clicks. Responses to low-frequency tones have also been reliably recorded provided the highpass filter setting of the amplifier is lowered to below 100 Hz (Suzuki and Horiuchi, 1977; Davis and Hirsh, 1979).

However, the problem of spectral splatter remains. Bauch, Rose and Harner (1980) investigated auditory evoked responses to clicks and tonepips at 1000, 2000 and 4000 Hz. Wave V emerged as the best indicator of auditory sensitivity with an inverse relationship between wave V latency and intensity, and between wave V latency and frequency. That is, as both intensity and frequency of the stimulus decreased, latency of the ABR wave V increased. The prolongation of latency with decreasing tonepip frequency indicated that the response was generated more apically on the basilar membrane. Tonepips with a short stimulus onset time (1 ms) were gated at a negative-going, zero crossing of amplitude. Although the spread of energy was reduced by using the tonepip as compared to the click, the range of wave V latencies for the 1000 and 4000 Hz

tonepips demonstrated considerable overlap, indicating that responses were still being generated from overlapping regions on the basilar membrane.

Similarly, Schmer and Kinarti (1984), looking at evoked responses to tonepips and filtered clicks, found wave V latencies using filtered clicks at 600 Hz differed little from those to 4000 Hz filtered clicks. This was taken as evidence that the dominant ABR responses elicited by filtered clicks were being initiated at regions more basal than their presumed frequency-specific location on the basilar membrane. In other words, if the response to the 600 Hz stimulus was being initiated at the apical region of the basilar membrane corresponding to that frequency, then the latency would be longer due to the increased time for the travelling wave to reach that region. A major reason for this lack of frequency specificity is spectral splatter. That is, frequency-specific stimuli of sufficiently rapid onset required to elicit an ABR response produce a spread of acoustic energy from their nominal frequency to a wider range of frequencies. The shorter the rise time (the faster the onset) the greater the spread (Picton et al., 1979; Stapells and Picton, 1981). For example, Jacobson (1983) examined acoustic spectra of 500 Hz tonepips with linear rise/fall times of 1 - 4 ms. The frequency bandwidth was 140, 180, 250 and 390 Hz for rise times of 4, 3, 2, and 1 ms respectively.

Folsom (1984) found that frequency specificity is intensity dependent. Using filtered clicks, his study confirmed earlier findings that, in general, as stimulus intensity is increased, responses become dominated by discharges from basal neurons in the cochlea, regardless of frequency (Davis and Hirsh, 1976). Thus, at moderate to high intensities the high-frequency regions of the cochlea will respond to low-frequency stimuli even though the place of maximum response for these stimuli may be closer to the apex.

Another way of approaching the problem of gaining frequency-specific measures is to consider the responses of the individual auditory neurons that innervate the cochlea. Gorga and Worthington (1983) looked at frequency tuning curves (FTC) which plot threshold of firing of the auditory neuron as a function of frequency. There is a frequency for which each neuron has its lowest, or best, threshold. This is referred to as the characteristic frequency and is related to the place along the basilar membrane innervated by the fibre. At this characteristic frequency, there is a sharp tip, with threshold increasing rapidly as frequency moves away towards higher frequencies from the characteristic frequency. At frequencies lower than the characteristic frequency, threshold also increases, but not as steeply and a low-frequency "tail" region exists where threshold does not change significantly. Low-frequency tones at moderate intensities would therefore be effective stimuli for a

higher-frequency neuron. In other words, fibres with high characteristic frequencies can respond to low-frequency stimuli.

In summary, the ABR has been shown to be an effective tool for the assessment of hearing, particularly in young infants and difficult-to-test subjects who cannot give reliable behavioural responses to auditory stimuli. The need to use a stimulus of rapid onset to evoke the response has resulted in widespread use of a click stimulus. The broad energy spectrum of the click, however, results in a relatively wide frequency response along the basilar membrane, and thresholds obtained from click ABRs have been found to agree best with predictions of hearing in the higher frequencies (2 - 4 KHz), without yielding information about lower frequencies. This is the result of both stimulus characteristics and cochlear mechanics. Attempts to restrict the cochlear response to the frequency under study has involved the use of more frequency-specific stimuli such as tonepips, which have narrower acoustic spectra than clicks. Studies have shown, however, that even use of more frequency-specific stimuli such as tonepips may not provide adequate frequency-specific information, since the short rise times required for tonepip ABRs cause energy splatter.

One means to further reduce the energy spread of the tonepip stimulus is to use different gating windows which produce the modulation envelope of the stimulus. Most

evoked-potential instrumentation systems have linear onset and offset ramps which do not give optimal spectral concentration. This can be improved by the use of more appropriate envelopes, for example, cosine, exponential and Gaussian modulation (Hyde, 1985). However, in most clinical settings, the envelope is subject to equipment limitations. A more readily implemented means of increasing frequency specificity is the use of masking.

MASKING

The difficulties of achieving frequency specificity using tonepips or filtered clicks alone have led to the use of masking noise in an attempt to restrict the response from the basilar membrane to the region activated by the nominal frequency of the desired stimulus by "blocking out" or desynchronizing the response from other frequency regions.

Pickles (1982, p. 98) defines masking as "the general phenomenon by which one stimulus obscures or reduces the response to another". The underlying assumption is that the neurons responding to the masking stimulus are no longer available to respond to the tone. Theories of how this works include the "line busy" hypothesis whereby the responses of neurons to the masking stimulus make them unable to respond further when the masked stimulus is presented (Smith, 1979). A further postulation is that

suppression occurs; that is, rather than activating a fibre, the masking stimulus decreases its sensitivity to another stimulus and thereby produces a masking effect (Pickles, 1982).

Various forms of masking, including white/broadband, highpass-filtered and notch-filtered (band-reject) noise, have been used in attempts to restrict the area of response on the basilar membrane and produce more frequency-specific ABR measures.

White, Gaussian, noise is a signal composed of energy present randomly at all frequencies. Although its energy is continuous across the frequency range, the limits of the transducer (earphone) determine the spectral characteristics of the noise, effectively making it broadband noise. In this context, broadband noise refers to white noise that has passed through a separate bandpass filter before reaching the transducer. Highpass noise ideally contains only frequencies above the filter cut-off frequency. The effectiveness of highpass noise in masking only high-frequency regions in the cochlea results from the travelling wave and the response pattern (tuning curve) of single auditory fibres. These fibres show a steep high-frequency "edge". Thus noise in high-frequency regions can mask the responses of high frequency fibres without masking fibres with lower characteristic frequencies. Notched noise is white noise in which one band of

frequencies has been stopped or rejected, allowing responses to frequencies within the notch while masking responses to frequencies outside the notch.

Studies attempting to obtain frequency-specific ABRs have used both clicks and tonepips with masking noise. However, the advantage of using tonepips is that they provide a greater concentration of energy at the required frequency than do clicks, with less noise required to mask tones than to mask clicks (Stapells et al., 1985). This reduces the possibility of having to use noise intensities that exceed subject discomfort level in order to effectively mask the stimulus.

Masking has been shown to be effective in providing greater frequency specificity than using tonepips alone. Evidence for this is based on the reported changes in latency of the ABR waves when masking is introduced (Picton et al., 1979; Bauch et al., 1980; Gorga and Worthington, 1983). If the amount of change in the latency more or less matches the expected travelling wave delay, given the frequency of the stimulus, then it is assumed that the masking has restricted the response to the tonepip frequency region in the cochlea.

Notched noise has been used by several investigators (Picton et al., 1979; Stapells and Picton, 1981; Pratt and Bleich, 1982). Picton et al. (1979) evaluated the use of notched noise to mask the frequency spread of tonepips when

eliciting the ABR. Testing at the frequencies 500, 1000, 2000 and 4000 Hz, both normal-hearing adults and children with stable sensorineural hearing losses were assessed. Auditory thresholds obtained by ABR testing were found to closely approximate pure-tone audiometric thresholds, and were more frequency specific than those obtained using tonepips alone. For example at 500 Hz increased frequency specificity was demonstrated by comparing the ABR response with and without masking. Notched noise significantly altered the brainstem response to loud 500 Hz tonepips by producing a significant increase in the latency of the most prominent positive wave. The explanation given was that, in the absence of noise, the tonepip activated wide areas of the basilar membrane with the major positive peak of the response probably deriving from the more easily synchronizable regions of the basilar membrane that normally mediate high frequencies. Masking limited the response to the 500 Hz region of the basilar membrane.

The experimenters compared 500 Hz tonepip ABRs masked by white noise and notched noise. The results indicated that although the latency - and therefore the frequency specificity - of the response appeared to be the same, when the masking noise is more intense than 30 dB below the peak intensity of the tonepip, the response is of significantly greater amplitude in notched noise.

In a series of experiments designed to determine the optimal stimulation and recording techniques for ABR audiometry using tones, Stapells and Picton (1981) found similar effects to those reported in the Picton et al. study described above. When notched noise was used, wave V latency increased for both 500 Hz and 2000 Hz tonepips and amplitudes were reduced. The shift in latency at 2000 Hz was not as great as at 500 Hz. The probable explanations for this are the higher frequency specificity of the 2000 Hz stimulus, and that the response is limited as to how far it can shift to an earlier or more synchronizable region of the basilar membrane. This is because maximum basilar membrane response to a 2000 Hz tonepip occurs more basally than to a 500 Hz tonepip. Without masking, the travelling wave dynamics allow a greater spread of energy along the basilar membrane for a 500 Hz tonepip than for a 2000 Hz tone. Thus, although maximum stimulation for low-frequency tones is apical, the more easily synchronized basal regions will also respond to the 500 Hz tone. Response to the 2000 Hz stimulus cannot come from the apical regions to the same extent. Therefore, when masking is introduced to stop responses outside of the nominal frequency, it has a greater effect on 500 Hz latency than on 2000 Hz latency.

There is a danger when using notched noise that upward spread of masking from the low-frequency edge of the notch may cause masking effects in the notch itself, thus decreasing the effective amplitude of the tonepip. Upward spread of masking refers to the ability of low-frequency

tones to mask higher tones, by exciting a wide area along the basilar membrane as the travelling wave moves apically toward the point at which it reaches its maximum (Trees and Turner, 1986). For example, Stapells et al. (1985), have found significant reductions in the amplitude of the ABR to 2000 and 4000 Hz tones at high intensities when presented in notched noise. While this is most likely due to removal of an underlying broad response to the low-frequency spread of energy in the tone when masking noise is used, the authors point out the possibility that some degree of masking at the frequency of the notch could also contribute to the decrease in amplitude.

Hyde (1985) also expresses reservations about using notched noise given the possibility of basal spread of masking from the low-frequency noise spectral regions, and resulting interaction between the masking noise and tonepips. They suggest that the problem of spread of masking would be avoided by the use of highpass-filtered noise for low-frequency ABR audiometry.

Kileny (1981) used highpass noise to study the degree of frequency specificity of responses elicited by 500 Hz and 1000 Hz tonepips. Cut-off frequencies of the maskers were 1500 Hz for the 500 Hz tonepips and 2000 Hz for the 1000 Hz tonepips. ABRs were also recorded to tonepips without masking, as well as to unfiltered clicks. When presented in quiet, wave V latencies for the tonepip stimuli differed little from wave V latencies for clicks, suggesting common

origins on the basilar membrane. When presented in highpass noise however, wave V latency shifted, suggesting the responses were originating from apical low-frequency regions. These results demonstrated that highpass masking could be used to obtain frequency-specific ABRs.

Gorga and Worthington (1983) suggest a limitation of highpass masking noise when applied to hearing-impaired subjects. With reference to tuning curves of single auditory fibres, changes have been noted as a result of cochlear lesions. These include an elevation of threshold at the characteristic frequency and reduction in sharpness of the tip of the curve. In such cases, thresholds to low-frequency stimuli may not be elevated to the same extent by noise as is observed for normal high characteristic-frequency fibres. Consequently highpass masking noise may be unable to eliminate the responses of fibres with characteristic frequencies higher than the stimulus frequency, in impaired ears.

One disadvantage of highpass noise is that it is inappropriate for high-frequency tones where the lack of specificity is in the opposite direction to that controlled by the noise. Brief tones presented at high frequencies may evoke responses through the spread of energy into the low frequencies (mainly in cases of high-frequency cochlear loss where the unimpaired basal regions of the cochlea will respond to the high-frequency stimulus). Stapells et al.

(1985) suggest a possible compromise of using notched noise for middle- and high-frequency stimuli, and highpass noise for the lowest frequency to be examined.

Another approach is to use white noise as the masking stimulus. Beattie and Boyd (1985) compared response detectability and latency of ABRs for tone bursts in quiet, notched noise and white noise. Latency differences between quiet and noise conditions were obtained only at higher intensities. This was presumably because at lower intensities the energy in the frequency bands adjacent to the tonepip frequency was below the threshold of audibility. When the notched noise and broadband noise conditions were compared, no significant changes in latency were observed. Auditory brainstem responses were obtained as readily with tonepips presented in broadband noise, notched noise or quiet. However, the advantage of using noise (whether notched or white) was that evoked responses were isolated to more frequency-specific areas of the cochlea than when tone bursts were presented in quiet. When notched and white noise conditions were compared, no significant differences in latency were observed. This latter finding was consistent with the research of Picton et al. (1979), and suggests that the additional stimulus energy within the notch (using notched noise) did not yield significantly better results (lower thresholds) than when the notch was filled with masking noise. Beattie and Boyd

suggest white noise is preferable because it can be clinically implemented with less complex instrumentation and calibration than notched noise.

To summarize, the lack of frequency specificity available from ABRs recorded to transient stimuli, such as filtered clicks or tonepips alone, has led to the use of various masking techniques. By introducing masking noise simultaneously with the tonepip stimulus, the area of response on the basilar membrane is assumed to be restricted to the region activated by the nominal frequency of the stimulus. Evidence for this is based on studies of ABR wave latencies to tonepips in quiet compared to tonepips in noise. If a shift of latency occurs when noise is introduced, and the amount of shift matches the expected travelling wave delay given the frequency of the stimulus, then it is assumed that the cochlea region able to respond to the stimulus has been restricted by the masking. This increased frequency specificity has been demonstrated using a variety of masking procedures including white/broadband noise, highpass or notch-filtered noise. While notched noise appears to result in measurement of larger response amplitude than broadband noise, possible spread of masking from the low-frequency edge of the notch may present a problem. The more readily implemented use of white/broadband noise has been recommended, since there appear to be no significant differences in ABR wave latencies when either notched or white/broadband noise is used.

MASKING LEVELS AND APPROXIMATION OF ABR THRESHOLDS TO AUDIOMETRIC THRESHOLDS

The utility of the ABR as a means of assessing hearing sensitivity depends on how well audiometric thresholds can be predicted by the evoked response.

Mention should be made of some of the different ways stimulus levels (and hence thresholds) are expressed. Expressing the level in dB HL (hearing level) refers to a scale where the reference is the average hearing threshold for the particular stimulus, as measured on a group of young, normal-hearing listeners (for example, re ISO Standard 389-1985 (E)). Intensity levels may also be expressed in dB SL (sensation level) - 0 dB SL refers to an individual's threshold for a particular sound. These are both relative scales.

In contrast, stimulus levels may be expressed in absolute terms. ABR stimuli (tonepips and clicks) are commonly calibrated in dB peSPL (peak equivalent sound pressure level) an absolute scale which refers to the sound pressure level (re 20 micropascals) of a continuous pure tone with a peak-to-peak voltage equal to the peak-to-peak voltage of the stimulus. For the types of stimuli commonly used in ABR audiology, the difference between peSPL and dB HL is normally in the range of 20 - 40 dB (Arlinger, 1981).

Stimulus levels used in ABR audiometry may also be based on a behavioural threshold reference, being the mean behavioural threshold for ABR stimuli (clicks or tonepips) as measured in a group of normal-hearing young adults. This is termed dB nHL and is a practical solution to the difficulties involved in measuring the intensity of very brief stimuli with standard clinical sound level meters. The dB nHL reference for ABR is analogous to the standard audiological procedure of defining hearing loss in dB HL.

ABR thresholds are generally defined in dB nHL, but since ears with 0 dB HL pure-tone thresholds usually have ABR thresholds of 15 - 20 dB nHL, it is difficult to compare ABR thresholds directly to pure-tone thresholds (Berlin and Dobie, 1979). When prediction of hearing loss is based on the ABR, degree of loss is estimated from the elevation of ABR thresholds. Many studies have attempted to compare the ABR to audiometric thresholds, to validate the use of this technique as an objective means of hearing measurement.

A typical means of doing this, as outlined by McGee and Clemis (1980), involves the determination of audiometric thresholds using pure-tone audiometry (ANSI Standard S3.21-1978). Normal-hearing thresholds are generally 15 dB HL or less at octave frequencies from 250 - 8000 Hz. ABRs are recorded to clicks, or tonepip stimuli at each frequency being tested, or to a reduced frequency range (generally 500 - 4000 Hz). The wave V component of the

brainstem response is of primary interest, and its "threshold" is determined by recording responses down to a level at which no repeatable wave V is present. Although computer-based threshold determination procedures exist, equipment limitations generally preclude the widespread used of these in most clinical settings (Mason, 1984). Judgements of response presence or absence are generally made by experienced researchers or clinicians based on such characteristics as response replicability and morphology. McGee and Clemis (1980, p. 297) define threshold as "the peak sound pressure level halfway between the lowest level at which a response occurred and the highest level at which no response could be detected". Gorga, Abbas and Worthington (1985, p. 106) define ABR threshold as "the lowest intensity that resulted in a replicable ABR". The latter definition is widely accepted for clinical use.

Using clicks alone, most studies have established that ABR thresholds correspond to hearing sensitivity in the frequency region of 2 - 4 KHz, but have not been able to provide information about low-frequency hearing (Kileny, 1981; Davis and Hirsh, 1976). Using tonepips, however, has yielded more frequency-specific information.

Mitchell and Clemis (1977) measured brainstem responses to unmasked 2, 4, and 8 KHz tonepips. Average ABR thresholds were reported as approximately 12 dB greater than behavioural thresholds (dB nHL) at the same frequencies.

Suzuki, Hirai and Horiuchi (1977) studied ABR responses to 500, 1000, 2000 and 4000 Hz tonepips. For normal-hearing subjects, up to 73% of the recorded traces yielded a recognizable and repeatable ABR at 10 dB SL.

Davis and Hirsh (1979) using tonepips at 500, 1000, 2000 and 4000 Hz reported ABR results which allowed the prediction of audiometric thresholds to within 10 dB.

Sohmer and Kinarti (1984) recorded ABRs to filtered clicks in highpass- and notch-filtered noise for subjects with hearing loss. For those subjects with high-frequency losses, the range of average differences between ABR thresholds and pure-tone audiometric thresholds was -0.9 to 2.4 dB, and for low-frequency losses, 23 - 38 dB.

Most studies report close agreement between perceptual and physiological thresholds (that is, prediction of audiometric thresholds from ABR thresholds within 10-20 dB). However, this does not seem to hold in the case of steeply-sloping cochlear hearing loss.

For example, Picton et al. (1979) demonstrated that in patients with steeply-sloping, high-frequency losses, thresholds obtained using brief tones alone may significantly underestimate the degree of loss. This is presumably because the brief high-frequency tonepip, with its spread of energy, is processed by the more normally functioning low-frequency region of the cochlea. Therefore

masking is required to completely eliminate any response from the low-frequency apical region of the cochlea. In an extensive study, these authors evaluated recording of brainstem responses to tonepips presented in notched noise, as a means of obtaining frequency-specific auditory thresholds. Tonepips were calibrated behaviourally (dB nHL) and referred to as "perceptual thresholds" by the authors. For normal-hearing subjects, the ABR could be identified to within 10 - 20 dB of perceptual threshold. For audiological purposes a difference of 10 dB is not considered very large. For subjects with high-frequency cochlear hearing loss, ABR thresholds were within 20 dB of perceptual threshold. Two exceptions were a subject with mid-frequency loss, where severity of loss was overestimated at 500 Hz and 1000 Hz, and a subject with good mid-frequency hearing (1000 Hz) but a high- and low-frequency loss, in which case the loss at 2000 Hz was underestimated. Thresholds obtained using tonepips alone and tonepips in notched noise were compared. Results showed that ABR thresholds to tonepips in noise (dB nHL) more closely approximated conventional audiometric thresholds, than did tonepips alone.

Therefore, without masking, the tonepip ABR may underestimate the degree of high-frequency loss. Low-frequency thresholds may also be inaccurately assessed by overestimation of the degree of loss.

Hayes and Jerger (1982) studied the predictive accuracy of the ABR to tonepips in both normal-hearing and hearing-impaired subjects. Prediction of hearing sensitivity was based on the comparison of ABR thresholds (dB nHL) to tonepips at 500, 1000, 2000 and 4000 Hz, to pure-tone audiometric thresholds. For normal-hearing subjects predictive accuracy was high. However, in the case of cochlear loss, predictive accuracy was less, with the major source of predictive error in the data being for the 500 Hz tonepip. In most hearing-impaired subjects, the ABR threshold at 500 Hz overestimated degree of hearing loss. The extent to which hearing loss was overestimated varied depending on the contour of the pure-tone audiogram. As slope of the audiogram increased, especially between 500 and 1000 Hz, overestimation of hearing loss at 500 Hz increased.

To use ABR audiometry to accurately predict the pure-tone audiogram, it appears that masking is desirable. This is particularly important in the case of cochlear losses. However, there must be certainty that the regions in the cochlea responding to frequencies other than the frequency under test, are being effectively masked. Effective masking means that a test signal is adequately masked by the presence of a masker. In this study the effective masking level is defined electrophysiologically as that which completely "blocks" the response (obliterates the ABR) from all frequencies other than a narrow band at the test frequency. The "effectiveness" of the masking will depend

on such factors as the bandwidth and the overall level of the masking noise. Studies that have established ABR thresholds to tonepips in noise, have used a variety of masking noise levels.

Kileny (1981) compared ABR thresholds (dB nHL) elicited by 500 and 1000 Hz tonepips in highpass noise to audiometric thresholds (dB HL), with the highpass noise set to an overall sound pressure level (SPL) equivalent to the peak SPL of the tonepips. He found close approximation to audiometric thresholds in both normal-hearing subjects and subjects with high-frequency losses.

Klein (1986) measured responses to 4 KHz tonepips using broadband noise (1 - 20 KHz). Setting the overall SPL of the noise at 10 dB below the pesPL of the tonepip was found to be effective.

Picton et al. (1979), studying subjects with hearing loss, used notched noise set at 15 - 25 dB below the pesPL of the tonepips. For subjects with high-frequency hearing loss setting the noise at 25 dB below the pesPL of the tonepip resulted in a small brainstem response occurring below the level of perceptual threshold, indicating insufficient masking. Setting the noise 15 dB below the signal yielded ABR thresholds closely approximating the subjects' perceptual thresholds (dB nHL). The conclusion

was that for effective masking, the difference between the overall SPL of the masking noise and the peSPL of the tonepips should be no more than 15 dB.

In a more recent study, Stapells et al. (1985) found that by increasing the onset time of the tonepips from 1 to 2 ms and reducing the notch width from 2 to 1 octave, noise levels could be reduced to 23 dB below the peSPL of the tonepips. In contrast, effective masking when using highpass noise and 500 Hz tonepips required SPL intensities of 8 dB greater than the peSPL of the tone, to ensure complete masking. This was more than reported above in Kileny's study.

While reported differences in effective masking levels may depend in part on type of noise and stimulus parameters used, methodology is also important. Unfortunately few published studies have included details of how masking levels were determined.

For example, Kileny (1981) assumed masking would be effective if the highpass noise was set to an overall SPL equivalent to the peak SPL of the tonepips, but gives no details as to whether this assumption was validated experimentally.

Klein (1986), in the study previously described, determined masking levels by bandpass filtering the noise and adjusting it in level to just completely mask the ABR.

This requires visual inspection of wave forms and judgment of presence or absence of a response. While this is an accepted clinical and research procedure (Hayes and Jerger, 1982; Beattie and Boyd, 1985; Folsom, 1985) the results depend on subjective decisions, and details of the decision-making process were not given.

Picton et al. (1979) determined effective masking levels from a systematic study of the effects of varying amounts of notched masking noise on 500 Hz and 4000 Hz tonepip ABRs. Keeping tonepip intensity constant, ABRs recorded with and without notched noise were compared. The pre-filtering overall noise SPL was varied between 5 dB above and 45 dB below the peak SPL of the tonepip. Variation in the amplitude and latency of the resultant ABRs was measured, with latency changes taken as indicative of the cochlear region responding to the tonepip. For normal-hearing subjects, results showed notched noise masking at intensities between 5 and 35 dB below the tonepip resulted in the 500 Hz ABR deriving from the apical regions of the cochlea (based on latency measures). The largest and most consistent wave V responses occurred with noise intensities at 25 dB below the tonepips. For subjects with high-frequency hearing loss, sufficient masking was required to stop the more normal-hearing low-frequency (500 Hz and 1000 Hz) regions of the cochlea from responding to the high-frequency (4000 Hz) tonepip. For all subjects, an ABR threshold (dB nHL) in response to 4000 Hz tonepips which closely approximated audiometric

threshold at that frequency was accepted as evidence of effective masking. In subjects with high-frequency hearing loss, when the masking noise was set at 25 dB below the peak SPL of the tonepip, a small brainstem response was still evident below audiometric threshold. Increasing the noise level to 15 dB below the tonepip peak SPL produced a threshold closely approximating the 4000 Hz audiometric threshold. Thus, a masking level 15 dB below the peak SPL of the tonepip was recommended.

However, while adequate masking was inferred from the latency changes of the ABR and approximation of ABR thresholds to audiometric thresholds, these results do not necessarily indicate that sufficient masking was present to completely stop other frequency regions of the cochlea from contributing to the recorded ABR to a given frequency.

Another method of establishing effective masking is to determine the levels of noise that perceptually mask tonepips. Stapells (personal correspondence , January, 1987) reported levels of the white noise required to just mask the perceptual responses to 500, 1000, 2000 and 4000 Hz tonepips at 10/second. Overall masking levels (dB SPL) ranged from 2 dB above to 6 dB below the pesPL of the tonepips.

To summarize, an important use of the ABR has been to establish hearing sensitivity in subjects who are otherwise unable to give reliable behavioural measures of hearing.

This means that the ABR must yield a measure of hearing which will indicate the perceptual auditory ability of the subject. Attempts to validate this measure have involved the comparison of ABR thresholds (the lowest intensity that results in a replicable ABR) to known audiometric thresholds. By using tonepip stimuli in the presence of masking noise, many studies have recorded frequency-specific ABRs which have been used to predict audiometric thresholds. To be sure that the ABR response is frequency specific however, masking must be "effective". That is, one must be sure that the ABR is restricted to the cochlear region corresponding to the frequency being tested. There has been considerable variation in the levels of noise used in studies that have attempted to determine ABR thresholds as a measure of hearing sensitivity. While differences in reported effective masking levels may result from variations in stimulus parameters and types of masking noise, the method used to determine masking "effectiveness" is important. The validity of the resultant ABR thresholds and consequent comparison to audiometric hearing levels, requires assurance that adequate or "effective" masking has been used to yield a frequency-specific response.

Unfortunately, many studies reporting masked ABR thresholds fail to give details of how the level of masking noise was determined, or have chosen a level arbitrarily. Given the importance of "effective" masking when obtaining frequency-specific ABR thresholds, and the lack of reported detail in many studies concerning how masking levels have

been established, the present study was designed to determine effective masking levels for the ABR in normal-hearing subjects using tonepips at 500, 1000, 2000 and 4000 Hz and white noise masking.

Because of the standard clinical practice of using a nHL reference for ABR stimulus levels, a behavioural calibration of the tonepips was undertaken to establish 0 dB nHL levels.

Before discussing further the aims of the present study, consideration must be given to three areas important to validation of the study. These are:

- (1). Choice of stimulus and recording parameters for ABR measurement.
- (2). Physiological (ABR) versus perceptual (behavioural) response comparisons.
- (3). Applicability of adult results to infants.

STIMULUS AND RECORDING PARAMETERS

Filtering

The electrophysiological response to the ABR stimulus is extracted from the filtered, amplified surface potentials recorded from electrodes attached to the scalp. As is the case with most bioelectric potentials, the ABR is enveloped in a background of competing electrical activity (electroencephalographic (EEG) and myogenic), the voltage levels of which may exceed those of the ABR many times over. To detect the ABR, the response is averaged over many presentations (often 1000 or 2000 repetitions). Averaging allows extraction of a small target signal from random noise. However the morphology of the averaged response will have poor resolution unless the frequency response of the recording system is set to reject a maximal amount of electrical interference. Bandpass filtering is therefore used to optimize clarity of the evoked response by increasing the signal-to-noise ratio. In ABR testing the appropriate cut-off frequencies for bandpass filtering are determined by the frequency content of the ABR itself. Studies have shown that the brainstem evoked potentials to clicks of moderate intensity (40 - 70 dB SPL) contain most energy in the 50 - 250 Hz region, with a shift toward even

lower frequencies at lower intensity levels. Therefore, any highpass filtering in this frequency range will alter the morphology of the response (Stapells and Picton, 1981).

The lack of success of early attempts to record ABRs to low-frequency stimuli were found to result from setting the highpass filter cut-off frequency too high (Davis and Hirsh, 1976). Subsequent widening of the bandpass filter from 150 Hz to a 40 Hz highpass setting produced an identifiable wave V to 500 Hz tonepips (Davis and Hirsh, 1979).

Several investigators have studied the optimum highpass filter setting. Suzuki and Horiuchi (1977) studied the effects of different highpass-filter settings on tonepip ABRs using 500, 1000, 2000 and 4000 Hz tonepips, confirming the necessity to use a low highpass-filter setting to obtain measurable responses to low-frequency stimuli. They suggested setting the highpass filter at 50 Hz or less, since the dominant frequency component of the brainstem response for 500 Hz tonepips is significantly lower than for 2000 Hz tonepips.

In addition to the highpass filter cut-off frequency, the roll-off slopes of the filter also affect the ABR. Roll-off slope refers to the rate at which the filter rejects frequencies above or below the cut-off filter setting. The optimal highpass-filter setting of 50 Hz or less, suggested by Suzuki and Horiuchi (1977), was for

6 dB/octave roll-off slopes. For higher roll-off slopes, marked alterations in response morphology have been reported. For example, when using a 50 Hz cut-off with a roll-off slope of greater than 50 dB/octave responses to 500 Hz tonepipes contained a prominent negative wave (Suzuki and Horiuchi, 1979).

Stapells and Picton (1981) did a series of experiments to determine optimal stimulation and recording techniques for ABR audiometry using tones. Using normal-hearing subjects, they studied the effects of different amplifier highpass- and lowpass-filter settings and roll-off slopes on responses to 500 Hz tonepip ABRs. The latency and amplitude of wave V decreased as either cut-off setting or roll-off slope of the highpass filter increased. The largest response to low-frequency tones was recorded using a highpass setting of 10 - 20 Hz and less than 24 dB/octave roll-off slopes. This allowed a large, clear vertex positive wave to be recorded. At higher highpass settings and steeper roll-off slopes, a smaller response was recorded and the prominent response became a vertex negative wave.

Mason (1984) did a similar study looking at the effects of highpass filtering on click-evoked ABRs. Although a lower lowpass filter was used (1000 Hz) and higher roll-off slopes (36 dB/octave), the results were consistent with Stapells and Picton's. A 20 Hz highpass-filter setting was optimum for best detection of the ABR when testing close to

hearing threshold. At this setting a large, repeatable peak was produced (arising from high response amplitude and low background electrical activity). Increasing the highpass filter caused a reduction in amplitude. Mason also noted that lowering the highpass setting to 10 Hz or below is undesirable, since noise (background electrical activity) levels would be increased further due to excessive EEG activity present at these frequencies.

Brainstem response morphology is also susceptible to lowpass filter settings, although not to the same extent as to highpass settings. Stapells and Picton (1981) found optimal waveform resolution at a setting of 3000 Hz. Increasing this to 10,000 Hz has been shown to produce decreased wave latencies, while reducing the setting to 1500 Hz results in increased latencies. At settings less than 1500 Hz, wave morphology may be totally disrupted (Cacase, Shy and Salya-Murti, 1980). A lowpass setting of 3000 Hz is routinely used in ABR measurement for diagnostic and audiometric purposes (Beattie, Moretti and Warren, 1984; Davis and Hirsh, 1979; Burkard and Hecox, 1983).

Subject State

A primary problem in the clinical application of the middle latency response and late response has been their instability as a function of subject state. For example, response morphology and latency have been shown to vary

according to the subject's degree of attentiveness (Okitsu, 1984). In contrast, the ABR is relatively state-independent (Jerger and Jerger, 1985). A study by Osterhammel, Shallop and Terkildsen (1985), which compared ABRs from sleeping subjects to ABRs measured on the same subjects when awake, found only minor changes in latency. Nevertheless, excessive myogenic activity and movement artifacts may reach amplitudes of several hundred microvolts and therefore easily swamp the small auditory brainstem response (Arlinger, 1981). To reduce interference, the subject should be in a still and relaxed state. Subject state is especially critical to obtain recognizable responses at low intensities (Beattie et al., 1984). Most studies indicate testing was performed in "relaxed subjects" - for example, reclining on a bed or comfortable chair with eyes closed (Kileny, 1981; Hayes and Jerger, 1982; Folsom, 1984). Others have reported optimal responses when subjects were sleeping (Davis and Hirsh, 1979; Gorga et al., 1984; Takagi, Suzuki and Kobayashi, 1985).

Electrode Placement

The choice of electrode site can also affect ABR wave morphology, although investigators do not agree on a preferred electrode placement.

Beattie et al. (1986) examined the effects of electrode placement on the early auditory evoked responses in normal-hearing subjects. The positive (non-inverting), negative (inverting) and ground (common) electrodes were studied in 10 commonly used combinations (that is, commonly used for clinical and research applications). No mean differences in latencies were observed for waves I, III and V with any of the 10 combinations, nor were there significant wave I or III amplitude differences. Placement of the positive electrode on the vertex however, produced a significantly larger wave V amplitude as compared to placement on the upper forehead.

Stapells and Picton (1981) found that placement of the reference (negative) electrode near the cochlea (on mastoid, earlobe or in the external auditory meatus) was most desirable to record clear waves I and III. Inter-electrode impedances below 3000 ohms were also recommended to maximize the signal-to-noise ratio.

Stimulus Rise/fall times

When using tonepip stimuli to record ABRs, an important consideration is the interaction that occurs between the temporal characteristics of the stimulus and its frequency spectrum. The spectra of tonepips are dependent on stimulus rise/fall times. The shorter the rise/fall time (time from stimulus onset to maximum or peak amplitude),

the greater the energy spread to frequencies other than the nominal frequency. In other words, rise/fall time determines the amplitude relationship between the main (centre) lobe and side lobes of the tonepip spectrum (see Figure 2, p.7). Increasing the rise time reduces this energy spread and makes the stimulus more frequency specific (Gorga and Worthington, 1983). The ABR however, being an onset response, requires a relatively brief stimulus with rapid rise time to elicit it (Hecox, Squires and Galambos, 1976). Stapells and Picton (1981) found rise times of >5 ms produced a significantly attenuated brainstem response, with increased latency and reduced amplitude of wave V. Consequently, when eliciting ABRs to tonepipes, a compromise is required between frequency specificity and optimization of the brainstem response. This means selecting rise/fall times that are sufficiently long to provide adequate frequency specificity, yet short enough to elicit well-defined responses.

Several studies have investigated the effects of rise/fall time on the ABR. Hecox, Squires and Galambos (1976) varied the rise/fall times of bursts of white noise. Rise/fall times of a 30 ms signal presented at 60 dB SL were 0, 1, 2.5, 5, and 10 ms. Wave V latency was delayed with increasing rise time, but was unaffected by fall time. Wave V amplitude however, was insensitive to changes in rise/fall time.

Similarly, Stapells and Picton (1981), using tonepips, found significant increases in wave V latencies with increasing rise time. In this study amplitude was also affected, showing a decrease at longer rise times, particularly times > 2.5 ms. They recommended rise times of 5 ms or shorter for tonal stimuli.

Kodera, Yamane, Yamada and Suzuki (1977) observed responses to 1000 Hz tonepips using rise/fall times as great as 10 ms, but noted a broadening and decreasing amplitude as rise time increased from 0.25 ms to 10 ms.

Beattie, Moretti and Waren (1984) using 500 Hz and 2000 Hz tonepips, studied the effects of rise/fall times of 1, 2 and 4 ms. Varying the rise/fall times had little effect on the detectability of the waves. Consequently, a 4 ms rise/fall time was recommended because of its greater frequency specificity.

In contrast to using a constant rise/fall time across all frequencies, Davis, Hirsh, Popelka and Formby (1984) recommend using tones having rise/fall times of 2 cycles each and a plateau duration of 1 cycle - the "2-1-2" tonepip. One advantage of specifying rise/fall times in terms of a constant number of cycles, is that the spectra of the tones with different frequencies are equivalent when plotted on a logarithmic frequency axis. That is, the bandwidth of the energy in the tone, expressed in octaves, is constant across frequency. This provides uniform

frequency specificity and is consistent with the conventional audiometric practice of using a log frequency scale. In contrast, stimuli with temporal characteristics fixed in time, regardless of frequency, will have uniform energy splatter on a linear frequency scale. Thus, since frequency representation of the basilar membrane is non-linear, high-frequency stimuli will excite more narrow regions on the basilar membrane than stimuli with lower centre frequencies.

Takagi, Suzuki and Kobayashi (1985) in a study of the most feasible settings for tone burst rise/fall times supported Davis et al.'s suggestion that 2-1-2 stimuli be used. ABRs to tonepip stimuli, with a constant rise/fall time of 4 ms at all frequencies, were compared to ABRs from tonepips with rise/fall times corresponding to a constant two-cycle period. With rise/fall time held constant, the amplitude of the response decreased with increasing stimulus frequency. However, when rise/fall time was a constant number of cycles, amplitude remained stable across frequencies. The conclusion was that it is better to set the rise/fall time by a constant period of the chosen frequency because of the smaller inter-frequency differences in the amplitude of the response.

Stimulus Repetition Rate

Stimulus repetition rate (the number of presentations per second) has been shown to produce changes to the ABR . In general, increases in rate of stimulation above 20/second result in a decrease in amplitude for the early components of the ABR (waves I - III) but have little effect on wave V, until stimulus rate exceeds approximately 30/second (Schwartz and Berry, 1985). Wave latency also increases with increasing rate of presentation.

Stapells and Picton (1981) using a 10 Hz - 3000 Hz (24 dB/octave roll-off) filter setting, compared repetition rates of 10, 20 and 35/second. They recorded the highest wave V amplitude at a 35/second presentation rate. The clinical utility of using a fast presentation rate is the shorter test time necessary to measure the averaged response. Repetition rates of between 11 and 41/second are routinely used in clinical applications of ABR, with higher response rates generally used for paediatric ABR measurement (McGee and Clemis, 1980; Hyde, 1985; Weber, 1982). In a study by Jacobson (1985) wave V of the ABR was found to maintain approximately 85% of its original amplitude at rates up to 80/second.

Stapells et al. (1985) recommend a tonepip presentation rate of around 40/second. At this rate wave V and the "40 Hz" response were found to be superimposed, producing a larger response overall. The 40 Hz response refers to the

finding that higher stimulus repetition rates can lead to temporal overlap of longer latency responses in such a way that the earlier components of the evoked response to a particular stimulus are superimposed on the later components of the evoked response to a previous stimulus (Cohen, Schimmel and Rapin, 1971). In the case of the 40 Hz response, it has been found that the middle latency response to a stimulus is composed of a series of waves ranging in latency between 8 and 80 ms with a time interval of about 25 ms between successive waves. Therefore, if a stimulus repetition rate of 40/second (period of 25 ms) is used, the middle latency response to one stimulus will exactly align and superimpose on the middle latency response to a previous stimulus, leading to enhanced amplitudes (Sohmer and Kinarti, 1984).

Stimulus Intensity

A characteristic of the ABR is its sensitivity to the intensity of the acoustic stimulus. A decrease in stimulus intensity results in an increase in response latency of all ABR component waveforms (Schwartz and Berry, 1985). Based on this, latency-intensity functions (where a predicted latency increase should occur as stimulus intensity approaches a subject's hearing threshold) are used to aid in estimation of hearing threshold (Jacobson, Novotny and Elliott, 1980).

Worthington and Peters (1980) have calculated the probability of detecting wave V as a function of stimulus sensation level for normal listeners. Visual detection of wave V was possible in 75% of the cases at intensities between 10 and 20 dB SL and approached 100% at higher stimulus levels.

When determining the level of noise that effectively masks an ABR, the stimulus level is generally held constant, with masking noise varied in intensity. This produces effects on the ABR similar to those obtained by reducing the intensity of the stimulus (wave amplitude reduction and latency increases). In the present study, stimulus intensity was chosen at a low enough level to allow use of adequate masking without exceeding the subject's loudness discomfort level, yet high enough to give a clear unmasked response as a reference to which the responses in noise may be compared.

Stimulus Polarity

Stimuli, when transduced through an earphone, may begin with a positive (condensation) or negative (rarefaction) phase. This is commonly referred to as the polarity of the stimulus. Most studies suggest no alteration in the peak latency of wave V with either a condensation or rarefaction click stimulus (Ruth, Hildenbrand and Cantrell, 1982), although significant effects on the physical

characteristics of wave I in the direction of decreased latency, increased amplitude and improved resolution through using a rarefaction stimulus, have been noted (Stockard, Stockard, Westmoreland and Corifits, 1979).

Alternating onset polarity may be used as a means of cancelling the confounding effects of stimulus artifact that may be accepted through the recording electrodes, and does not appear to alter the response characteristics of the ABR wave V (Schwartz and Berry, 1985). In general, polarity seems to be a matter of clinical preference.

Summary

Bandpass filtering of background electrical activity (EEG and myogenic) is necessary to optimize clarity and resolution of the ABR. Since most energy in the evoked auditory brainstem response lies between 50 and 250 Hz, a low highpass setting and shallow roll-off slopes are desirable, particularly when measuring responses to low-frequency stimuli. A 20 Hz highpass setting has been recommended as optimal.

When recording ABRs to tonepips (or other stimuli) the resultant morphology and identifying characteristics such as latency are dependent on a number of stimulus parameters including rise/fall times, repetition rate, intensity and polarity.

Tonepip rise and fall times determine their frequency spectra. The shorter the rise/fall time, the greater the energy spread to frequencies other than the nominal frequency of the tonepip. Increasing rise time reduces energy spread, resulting in a more frequency-specific stimulus. The ABR, however, is a response to the onset of the stimulus and requires rapid rise time to be evoked. Consequently, obtaining frequency-specific ABRs using tonepips requires a compromise - selecting rise/fall times that are sufficiently long to provide adequate frequency specificity, yet short enough to elicit a well defined ABR. Rise/fall time may be expressed as a constant number of milliseconds, in which case < 5ms seems optimal, or as a constant number of cycles. In the latter case, rise/fall times of 2 cycles each and a plateau duration of 1 cycle - the "2-1-2" tonepip - have been recommended. This means that the bandwidth of energy in the tone, expressed in octaves, is constant across frequency.

Stimulus repetition rate can affect waveform morphology, resulting in decreased amplitude and increased latency of the ABR, if set at a high level. For wave V identification, a repetition rate of 30 - 40/second seems optimal.

As stimulus intensity is reduced, latency of the ABR increases. There will also be some reduction in amplitude, particularly of the early components (waves I-III). A level of 50 - 90 dB nHL should produce a clear waveform, at least for normal hearing subjects.

For wave V measurement, different stimulus polarities do not appear to produce significantly different effects. A rarefaction stimulus is recommended for clear wave I measurement. Alternating stimulus phase is useful to reduce electrical artifact in the recording.

Subject response state affects ABR measurement, particularly at stimulus intensities close to ABR threshold. Optimum responses occur when the subject is very relaxed or sleeping.

Stimulus parameters used in the present study were chosen to concur with the optimal settings recommended in the literature (within the limitations of the recording equipment). Highpass and lowpass filter cut-offs of 30 and 3000 Hz respectively were chosen (30 being the lowest setting available, without going below the recommended 10 Hz minimum), with a roll-off slope of 12 dB/octave. Constant period "2-1-2" tonepips were used subject to certain equipment limitations as outlined in Appendix 1(B). To minimize testing time, the fastest stimulus repetition rate recommended (40/second) was used. However, pilot testing of repetition rate with the equipment in the

present study suggested interference from the 50 Hz mains supply whenever multiples of 10 were used. The amplitude of 50 Hz interference was measured for repetition rates between 38/second and 42/second in 0.1/second steps. The 41.7/second repetition rate resulted in the least interference. Tonepips were presented at a constant level of 85 dB peSPL. This produced a clear ABR of large amplitude when presented without masking. Sufficient levels of white noise could also be introduced to establish masking levels for all subjects without exceeding subject discomfort level. Subjects were encouraged to relax and to sleep if possible. On the recommendation of Stapells et al. (1985), a click-evoked ABR was recorded for each subject prior to evaluating frequency-specific responses to tonepips, in order to ensure overall integrity of the auditory brainstem pathways.

PHYSIOLOGICAL AND BEHAVIOURAL COMPARISONS

One area of interest in the present study was to compare the levels of effective masking of the ABR response (electrophysiological masking) to levels of effective masking of subjects' response to tonepips established behaviourally (perceptual masking).

The comparison of ABR threshold responses to audiometric thresholds, as discussed previously, is one of the most common electrophysiological versus behavioural comparisons made in the area of evoked response audiology, since the utility of the ABR as a means of determining hearing sensitivity depends on knowing the relationship between hearing threshold and the brainstem response. The present study did not attempt to establish ABR thresholds for such a comparison. However the levels of masking found to be effective in this study can be used for future measurement of ABR thresholds determined in the presence of masking noise, to accurately assess hearing levels at frequencies of 500, 1000, 2000 and 4000 Hz.

A comparison that was of interest in the present study was to see whether the amount of noise necessary to eliminate the ABR response to tonepips was similar to the amount required to stop the subject from hearing the tonepips. It is not clear which method of establishing effective masking levels (behavioural or physiological) is more appropriate. If there is no difference, the method that is easier to

implement in a clinical setting would seem more appropriate. However, differences which may exist and the factors accounting for such differences, may contribute to our understanding of psychophysical versus physiological responses and affect the utility of applying electrophysiological data (such as tonepip ABRs) to behavioural data (such as perceptual measures of hearing sensitivity).

The use of a behavioural reference (dB nHL) to define ABR measurements is commonly found in audiological studies. For long duration (200 ms) pure tones, a behavioural reference (dB nHL) is equivalent to the standard reference thresholds (dB HL re ISO Standard 389-1985 (E)) for pure-tone audiometry.

Interpretation of the ABR based on behavioural threshold references, however, is complicated by other factors which suggest caution when making such comparisons: Weber, Seitz and McCutcheon (1981) point out that it is incorrect to equate behavioural click thresholds with the click's ability to elicit an ABR. Behavioural and electrophysiological responses to the same stimulus may be quite dissimilar, for example, increasing click rate reduces the period of silence between clicks and results in a perceptually louder stimulus which has a lower behavioural threshold. In contrast to this, increasing stimulus rate may produce a less effective stimulus in eliciting the ABR. This difference is related to the

finding that the ABR is an onset response whereas behavioural thresholds are influenced by the integration of acoustic energy over many milliseconds. The faster the click rate, therefore, the greater should be the difference between behavioural and ABR thresholds.

It is generally accepted that ABR potentials arise from the synchronous onset activity (discharges) from groups of nerve fibres in the auditory pathways and only those neural events occurring during the earliest portions of the stimulus contribute to these responses (Elberling, 1976). Thus the response is independent of stimulus duration (Hecox, Squires and Galambos, 1976). Harris and Dallos (1979) have shown by means of post-stimulus time histograms (plots of the discharges of a neuron as a function of time after stimulus onset) that for the first 100 ms after stimulus onset, the response changes. However, responses at stimulus onset are relatively independent of duration. Since ABRs are determined by neural activity occurring at stimulus onset, thresholds ought to be independent of duration.

Gorga et al. (1984) studied the effects of stimulus duration on ABR and behavioural thresholds. ABR and behavioural thresholds were obtained using 2000 Hz tone bursts with 0.5 ms rise/fall times and plateau durations ranging from 1 to 256 ms. An additional 512 ms duration was used for behavioural threshold estimates. Stimuli were presented at a slow presentation rate of 2 - 4/second.

Stimulus intensities for both ABR and behavioural thresholds were specified in dB peSPL. For both normal and hearing-impaired subjects, ABR thresholds remained relatively constant across all durations, differing by no more than the minimum step size of 5 dB. Behavioural thresholds, however, decreased with increasing duration at a rate of approximately 10 - 12 dB/decade time.

Behavioural and ABR thresholds for short duration (< 5 ms) stimuli showed good agreement. Comparison of behavioural thresholds for long duration stimuli and ABR thresholds at any duration, indicated that ABR thresholds were 20 - 25 dB above behavioural thresholds.

A number of studies have shown that behavioural thresholds depend on stimulus duration (Plomp and Bouman, 1959; Zwislocki et al., 1962). Thresholds for short duration stimuli may be as much as 25 dB higher than similar estimates for long duration signals (Watson and Gengel, 1969). This poses a problem when using behavioural references for ABR measurements since the reference response is altered by duration whereas the electrophysiological response is not (Picton et al., 1979).

In normal ears the audibility or loudness of a stimulus increases with increasing stimulus duration up to about 200 ms, indicating a summation of energy (Pedersen and Salomon, 1977). This is the phenomenon commonly referred to as temporal integration. Temporal integration experiments have shown for normal-hearing subjects, an 8 - 10 dB

improvement in threshold with every tenfold increase in tone duration up to between 200 and 300 ms (Plomp and Bouman, 1959).

Several studies comparing behavioural thresholds for short duration tones or clicks as a function of stimulus duration, have demonstrated temporal integration. Picton et al. (1979) established behavioural thresholds for tonepips at 500, 1000, 2000 and 4000 Hz in normal-hearing subjects. Using tonepips with rise/fall and plateau times of 1 ms (total duration of 3 ms) and a presentation rate of 40/second, average thresholds (dB pesPL) were 44 dB at 500 Hz, 34 dB at 1000 Hz, 31 dB at 2000 Hz and 29 dB at 4000 Hz. These levels represent 0 dB nHL at each frequency. On average, these thresholds were found to be 25 dB above normal-hearing thresholds for long-duration pure tones, as established by standard audiometric procedures (ISO Standard 389-1985 (E)).

Davis et al. (1984) also established behavioural thresholds using 2-1-2 tonepips at each of the frequencies, 500, 1000, 2000 and 4000 Hz, for a presentation rate of 40/second. Mean thresholds for normal ears (dB pesPL) were 18.4 dB at 500 Hz, 17.3 dB at 1000 Hz, 20 dB at 2000 Hz and 23 dB at 4000 Hz. Comparing these thresholds to those for long pulses of pure tones (rise/fall time of 20 ms and a plateau time of 200 ms), thresholds for the 2-1-2 tones were on average 13 dB higher than for the longer duration tones.

Although Picton et al. obtained higher dB peSPL values for thresholds corresponding to 0 dB nHL, both studies showed improved thresholds when longer duration tones were used, consistent with temporal summation of acoustic energy.

A similar result using clicks has been demonstrated by Stapells, Picton and Smith (1982). Normal behavioural thresholds for 100 microsecond clicks presented at a rate of 40/second, were compared at varying durations of the listening period, from 100 ms to 2 seconds. Increasing the listening period from 100 to 300 ms produced a 2.5 dB decrease in threshold, indicating temporal summation within this period. There was no significant change in threshold as the listening period increased from 300 ms to 2 seconds.

In addition to comparing thresholds for stimuli of varying duration, some studies of the effects of stimulus repetition rate on behavioural thresholds also suggests the involvement of temporal summation processes.

In the investigation by Picton et al.(1979) described above, perceptual thresholds to the tonepips at three different presentation rates of 40/second, 10/second and 1/second were established. Compared to the 1/second presentation rate, the more rapidly presented stimuli had lower thresholds, 3.5 dB less at 10/second and 5.3 dB less and 40/second on average. The authors suggest that the changes in threshold with different stimulus presentation rates are most likely due to the temporal integration

process occurring when tonepips are repeated within the integration time of 200 - 300 ms. Because of these effects, they suggest it is essential to know both the stimulus duration and the rate of presentation when assessing behavioural thresholds.

Stapells and his colleagues found similar effects on click behavioural thresholds when the presentation rate was varied. Threshold level was decreased by approximately 5 dB as repetition rate increased from 5 to 80/second. The authors suggested that increasing the rate at which brief stimuli are presented probably invokes temporal summation in a similar manner to increasing the duration of a continuous sound. The authors point out, however, possible differences between summation processes for the two types of stimuli (long duration pure tones and brief stimuli such as clicks or tonepips). Their study demonstrated a smaller summation effect for clicks (4.5 dB per tenfold increase in rate per second) than has been reported for continuous pure tones (8 - 10 dB per tenfold increase in duration). Other studies using brief tonal stimuli have reported effects of stimulus presentation rate that are similar to Stapells et al.'s results (Zerlin and Naunton, 1975; Yost and Klein, 1979).

In contrast to these findings, Davis et al. (1984) compared behavioural thresholds to 2-1-2 tones at repetition rates of 4 - 40/second. Although thresholds were reduced as repetition rate increased, they reported the effect small and not statistically significant.

Overall, studies have demonstrated that behavioural responses to brief stimuli are affected by duration, while the ABR, a physiological response, remains relatively stable across duration. Using a behavioural reference for measurement of ABR thresholds and consequent comparison to audiometric thresholds therefore, must be interpreted cautiously, keeping in mind the possible confounding effects of temporal integration.

The implications of temporal integration effects for behavioural versus physiological comparisons are also important when applying results from normal-hearing subjects to subjects with cochlear hearing loss, since studies have shown that differences in temporal integration exist for hearing-impaired subjects compared to normal-hearing subjects. In the study by Gorga et al.(1984), normal-hearing subjects showed greater improvement in behavioural threshold as a function of duration than did subjects with hearing loss (for whom thresholds changed at a rate of approximately 5 dB/decade time). Therefore less temporal integration was evident for

the hearing-impaired subjects. As a result the differences between ABR and behavioural thresholds to long duration stimuli were less than for normal subjects.

Gengel and Watsons' (1971) findings support the idea that cochlear hearing loss alters temporal integration.

Behavioural thresholds to pure tones at octave intervals between 125 and 8000 Hz, were measured using tone durations from 16 - 1024 ms. Studying normal or cochlear-impaired subjects, atypical temporal integration was observed for the subjects with hearing loss. The results suggested that when hearing loss was generalized over all or most of the audiometric frequencies, there is an accompanying generalized reduction in the ability of the auditory system to integrate the acoustic energy in brief sounds. In cases where hearing loss was limited to the high frequencies, the degree of loss seemed to determine whether or not normal integration was seen. These results were similar to those of Gorga et al. (1984). In addition, a systematic effect of frequency was observed indicating less efficient integration at high frequencies, since a given increase in duration produced less decrease in threshold than for the lower frequencies. This finding applied to both normal-hearing and hearing-impaired subjects.

Comparative studies of temporal integration in normal and hearing-impaired subjects need to be interpreted with caution because of the confounding effects of frequency and stimulus intensity. Pedersen and Poulsen (1973) report

normal temporal integration in subjects with cochlear hearing loss compared to normal subjects tested at the same intensity levels. However, Irwin and Purdy (1982) report temporal processing differences in impaired ears.

To summarize, interpretation of the ABR is often based on a behavioural reference (dB nHL). ABR thresholds have been found in most studies to agree closely with pure-tone audiometric thresholds (dB HL). Making physiological and behavioural comparisons however requires caution given the fact that the two responses result from different aspects of underlying neurological processes. Behavioural thresholds have been found to depend on stimulus duration while the ABR is an "onset" response and does not significantly alter with duration. Temporal integration - the integration of acoustic energy over time - has been shown to affect behavioural responses to brief stimuli such as clicks and tonepips. This is evidenced by perceptually louder stimuli as duration is increased up to 200 - 300 ms and results in decreased thresholds. This temporal summation has been shown to occur with both increases in stimulus duration, or increases in stimulus repetition rate (which effectively increases duration). In addition, hearing-impaired subjects have shown less temporal integration than normal-hearing subjects resulting in less improvement in behavioural threshold as a function of duration.

In the present study, a comparison of interest was that of effective masking levels established physiologically and behaviourally, for the ABR. This comparison was important because of the effects of temporal integration on behavioural thresholds and to determine the validity and utility of a behavioural calibration for the ABR. In addition, any differences in temporal integration between normal and hearing-impaired individuals could further complicate the interpretation of clinical ABR data that are referenced to behavioural thresholds. Such comparisons therefore need to be interpreted with caution.

ADULT AND NEONATE/INFANT COMPARISONS

A major reason for determining levels of masking in the present study was to provide accurate normative data (that is, signal-to-noise ratios), for future use in establishing a frequency-specific method of hearing assessment in infants. Use of the ABR has proven a clinical asset in the objective assessment of infants unable to respond to conventional audiometric testing. The disadvantage of the traditional click ABR technique, however, is that it does not accurately measure the hearing in different frequency regions, particularly the lower frequencies. A more frequency-specific technique is needed for the accurate assessment of hearing thresholds in infants. In addition, the choice of appropriate amplification devices to optimize the residual hearing of deaf infants depends on the accurate measurement of hearing at different frequencies. Early detection of hearing loss is important because delay will compromise the development of speech and language skills. Statistics for the age of detection of deaf children born in New Zealand during 1973 - 74 indicated 11% were detected within the first year of life (Keith, 1984). The same figures for 1982 - 83 showed an increase to 29% detection within the first 12 months of life. One of the factors contributing to improvement in detection was the advent of ABR audiometry during this period. Improved methods of testing, including frequency-specific ABR audiometry, should increase this detection rate further.

ABR audiometry has been used successfully in the assessment of infants for a number of years. Kaga and Tanaka (1980) obtained ABR and behavioural thresholds (as established by conventional paediatric behavioural response audiometry techniques) for infants between 0 - 12 months of age. ABR thresholds were constant over age whereas behavioural thresholds were initially higher but improved as age increased. At six months, there was agreement between the two measures within 15 dB (at six months of age, an infant's behavioural response becomes more reliable). This constancy of the ABR threshold and close agreement with behavioural threshold at six months was taken as evidence that the ABR is a valid threshold assessment tool.

Because of the limitations of using click stimuli, several studies have also been carried out using tonepips. Alberti et al. (1985) used 500 and 4000 Hz tonepips with masking and compared results to those using clicks. Clicks alone did not indicate low-frequency hearing loss (as established audiometrically on follow-up testing) while responses to tonepips did. This was accepted as evidence that this method does provide frequency-specific information.

The assumption of frequency specificity, however, as determined by the underlying physiology and mechanics of the cochlea, is based on adult correlative data. As many studies have shown, differences exist between the ABR of young infants and the adult ABR (mainly morphological and latency differences). These differences should be

considered when adult normative data are applied to infant testing. This is pertinent to future application of the levels of masking established in the present study to masking levels used for infant ABR measurement.

Jacobson (1985) reviewed technical, physiologic and pathologic conditions which affect response measurement in neonatal ABRs using clicks as auditory stimuli. Certain changes in the ABR have been noted as a function of maturation. In visual appearance, only three peaks are clearly measurable in the newborn, with the amplitude of wave III often larger relative to wave V. Between three and four months of age waves IV and V show signs of progressive separation, and by the end of the first year of life, the morphology of the infant response approximates that of the adult.

Latency measures are most important in the infant response and are also affected by maturation. In general, wave latencies decrease with increasing age, but at different rates. Wave V reaches adult equivalency at between 12 and 18 months while wave I latency approximates adult values by the third month. These differential effects on latency are attributed to improvements in peripheral (middle ear or cochlear) sensitivity and central (myelination and synaptic efficiency) transmission.

When looking at ABR amplitude compared to adult responses at stimulus presentation levels of equal intensity, the newborn wave V amplitude is approximately half the value.

Durieux-Smith et al. (1985) obtained normative data for babies in a neonatal intensive care unit, with results that were consistent with Jacobson's (1985) findings. Studying infants with gestational ages between 30 and 54 weeks, significant decreases in latency and increases in amplitude were noted with increasing age.

Several investigators have also looked at the effects of masking on the neonatal ABR compared to the adult ABR. Klein (1986) studied the effects of high and lowpass masking on waves I and V of the ABR in normal 2 - 4 week old infants and adults, to 4000 Hz tonepips. He found masking patterns were different for infants and adults, the largest difference evident for wave I. Lowpass maskers were found to be very disruptive of the infant wave I (producing latency shifts and amplitude reduction) while having little effect on the adult wave I. In contrast, highpass maskers were very disruptive of the adult wave I while having less effect on the infant wave I data. Klein proposed that this may be due to differences in tuning at the wave I and wave V level between infants and adults. Neural contributions which compose the infant wave I may be biased toward lower frequency fibres while the adult wave I represents a population of fibres which are biased toward higher frequencies.

Folsom (1985) studied the effects of simultaneous pure-tone maskers on ABR wave V latency and amplitude in three month old infants as a means of delineating the frequency specificity of these responses in the immature auditory system. Using pure-tone maskers and 1000 and 4000 Hz filtered clicks in addition to unfiltered clicks, Folsom obtained masking profiles (mean latency or amplitude of wave V of the ABR response as a function of masker frequency). Data were compared to similar latency and amplitude pure-tone masking effects for adult subjects, obtained under identical procedures (Folsom, 1984).

Masking profiles for infants showed clear differences when comparisons were made with adult data. Differences were noted for both the frequency range of the response region in the cochlea as well as changes in the extent of this region with increased stimulus intensity.

Independent of intensity, the pure-tone masking profiles from the infants showed a greater contribution of low frequencies than were shown in the adult profile. Hecox (1975) using highpass masking, reported a similar increase in low-frequency contribution to the infant ABR wave V. The high-frequency contribution for the ABR wave V in infants is therefore less than in adults.

Smaller absolute latency and amplitude changes with increases in intensity for the infant group also suggested a more restricted range of frequencies which contribute to this response.

Interpretations of such findings are difficult. Folsom suggests it may be that the infant's peripheral hearing apparatus is immature at this age and relatively insensitive to high-frequency sounds. However, possible mechanisms underlying differences in the neonatal auditory system can only be supposed based on analogies with anatomic/functional findings from studies of lower animals. For example, studies of neonatal and fetal chicks suggest low frequencies may be transduced in a more basal region in the immature system. It is possible that factors which may account for a slight restriction of the frequency range such as differences in basilar membrane tissue stiffness properties, or hair cell viability, may be involved.

Whatever the mechanisms, clear differences do exist between the ABR of the neonate and adult ABR's, with masking also producing differences in the response. Such differences need to be considered when applying normative adult data to infants.

OVERVIEW OF THE PRESENT STUDY

The utility of the ABR as a means of assessing hearing sensitivity has been amply demonstrated, particularly in the evaluation of neonates and other difficult to test subjects for whom reliable behavioural measures of hearing are unobtainable. The estimation of hearing sensitivity is based on a comparison of ABR thresholds to known pure-tone audiometric thresholds, as established on normal-hearing subjects. To adequately assess hearing, thresholds at specific frequencies need to be estimated. The use of frequency-specific stimuli, such as tonepips presented in masking noise, is purported to provide such estimates. The levels of noise, however, are critical to ensure the cochlear response is effectively restricted to the area on the basilar membrane corresponding to the nominal frequency of the stimulus. Masking levels cited in studies to date vary considerably and details as to how the levels were established are often omitted.

The primary aim of the present study was to accurately determine effective masking levels of the ABR to tonepips at the speech frequencies 500, 1000, 2000 and 4000 Hz, in normal-hearing adult subjects. It was the intention that these levels would provide normative data for further study into tonepip ABR threshold measurements, conducted by the New Zealand Health Department.

Also of interest in the present study was the comparison of ABR masking levels to those of behavioural responses to tonepips, to assess the most appropriate method of determining effective masking levels. Interpretation of a physiological versus behavioural comparison such as this, however, must take into account differences in the underlying neurological processes. In particular, temporal integration studies have shown behavioural thresholds to brief acoustic stimuli are affected by stimulus duration while ABR thresholds are not. The effects of temporal integration may apply also to masked thresholds and hence require consideration in the present study's comparison of masking levels. To assess possible effects of temporal integration, level of masking of the behavioural (perceptual) response to tonepips was compared at different stimulus repetition rates (effectively varying stimulus duration). In addition, the comparison of these perceptual masking levels to those for the ABR provides an indication of whether temporal integration must be considered in the interpretation of ABR measures when applied to behavioural measures of hearing.

METHOD

Subjects

Ten normal hearing adults (5 male, 5 female) aged between 18-30 years served as subjects. Hearing thresholds were <15 dB HL (re ISO Standard 389-1985 (E)) at the octave frequencies 250 - 8000 Hz, and there was no history of ear disease.

Apparatus

Pure-tone audiometry was performed on a Grason-Stadler 1704 audiometer calibrated according to the IEC Standard 645 (1979). A schematic diagram of the ABR equipment used is shown in Figure 4. Tonepips were generated by a NIC-1002 tone generator. Stimulus type (tone or click) and intensity was controlled by a NIC-1007 noise masking module, which also generated the click stimuli. Masking noise was provided by a Dawe Type 419C white noise generator (20 - 20,000 Hz), amplified by a Philips PM5171 amplifier/logarithmic converter and attenuated by a Marconi MF attenuator (model TF 2162). The overall level of the noise was 99.7 dB SPL for an attenuator setting of

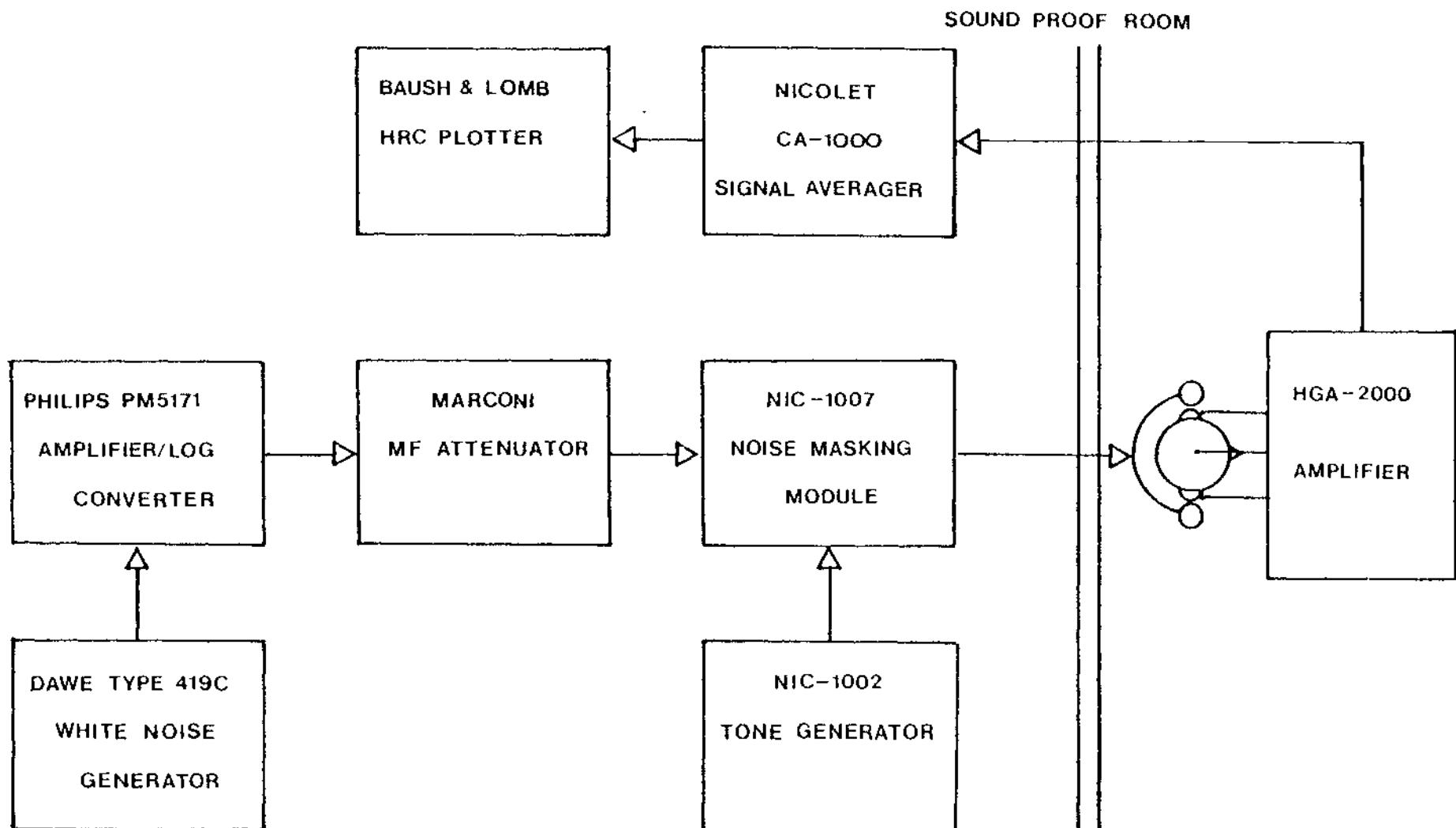


Figure 4. Schematic diagram of the ABR equipment used in the present study.

zero. The noise was fed into the external noise input of the NIC-1007 and mixed with the tonepip stimuli. Stimuli were calibrated according to the method outlined in Appendix 1. For tonepip ABR measurement, surface potentials were amplified (10^4) by a HGA-200A physiological amplifier and fed into a Nicolet CA-1000 signal averager. For tonepip ABR recordings the CA-1000 input bandpass filter was set at 30 - 3000 Hz (rejection rate 12 dB/octave). Each response was averaged over 1000 or 2000 trials using an analysis time of 25.6 ms. Input sensitivity was adjusted between ± 5 and ± 25 microvolts. With display gains of 16 or 32 the range of full scale display amplitudes was ± 0.2 to ± 1.6 microvolts. Artifact reject was used to exclude those responses with amplitude values exceeding 90% of the input sensitivity value (± 5 - ± 25 microvolts). ABR waveforms were plotted on a Baush and Lomb, Omniphotographic series HRC plotter.

The subject sat in a separate, sound-attenuated room. Ambient noise levels were within the maximum permissible levels cited in ANSI S3.1-1977 for air conduction audiometry. Stimuli were presented monaurally to the right ear by means of an earphone (Grason-Stadler TDH-49 mounted in MX-41/AR cushions). The voltage across the earphone was measured in a Brüel & Kjaer 4153 Artificial Ear and calibrated as outlined in Appendix 1(A).

For the electrophysiological measurements, silver EEG cup electrodes were applied, using Grass EC2 electrode cream for earlobe and forehead placements. Beckman EEG electrode adhesive paste was used for vertex placement being more abrasive and allowing better electrode contact through the hair on the scalp. The skin was first rubbed with alcohol and a light abrasive (Omni Prep paste). Inter-electrode impedances measured on an Amplaid electrode impedance tester were balanced and less than 3000 ohms.

For tonepip measurements, a 2 cycle rise/fall time and a 1 cycle plateau time was used, within the limitations of the equipment (see Appendix 1 (B)). Stimuli were gated on at a zero crossing of amplitude, with alternating onset phase.

Spectra of the white noise and tonepipes are shown in Figures 5 to 9. The white noise spectrum is relatively flat to approximately 9000 Hz falling within \pm 2 dB for frequencies up to 4000 Hz and dropping off at a rate of approximately 10 dB/octave up to 8 KHz. This reflects the bandpass characteristics of the TDH-49 earphone. The tonepip spectra show that the energy in the sidelobes adjacent to the nominal tonepip frequency was at least 25 dB less than the peak amplitude at the nominal frequency. Tonepipes having a constant number of cycles (Figures 6 - 8) show similar spread of energy to higher and lower frequencies. The exception is at 4000 Hz (Figure 9) where the spectrum is narrower. This was to be expected given

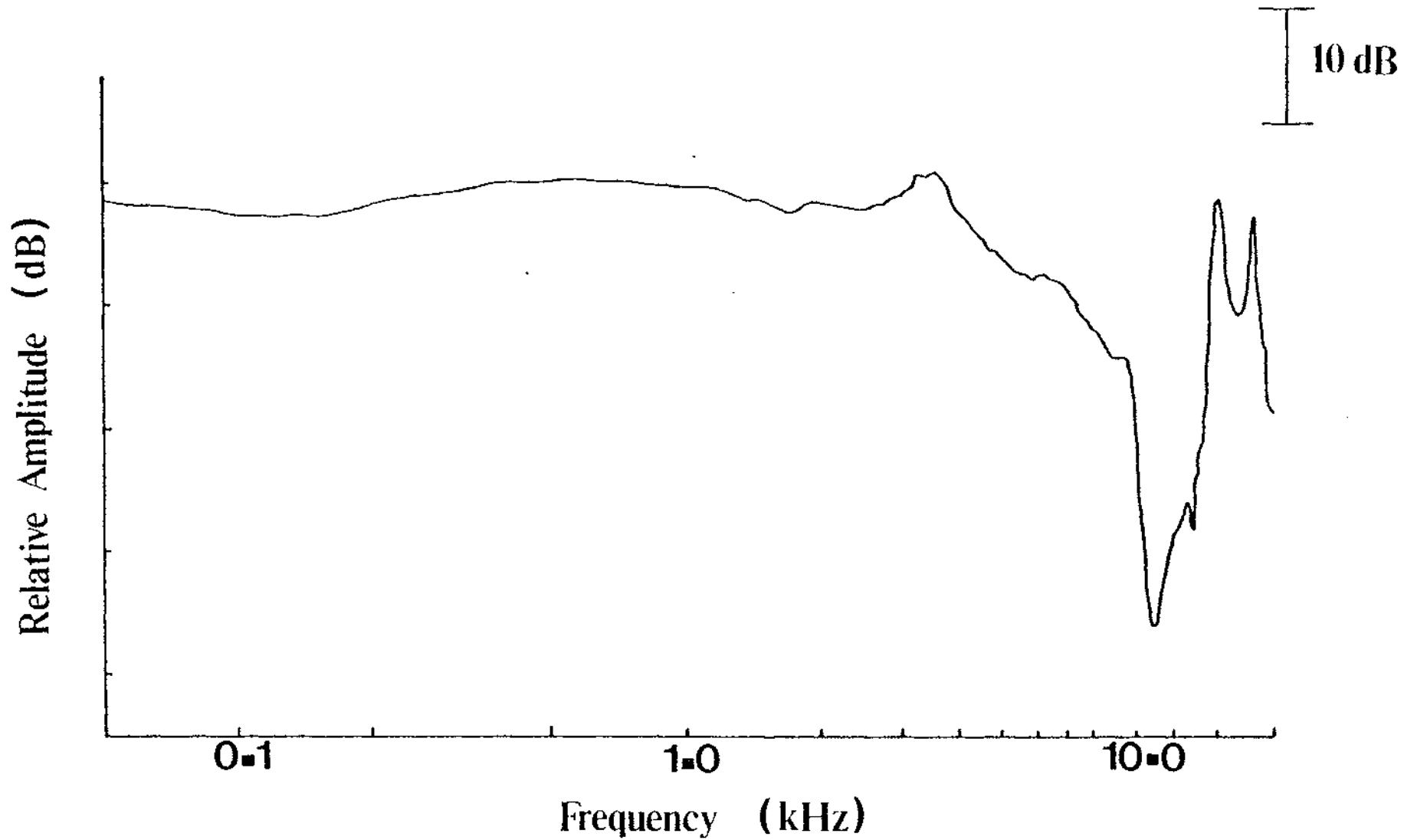


Figure 5. Acoustic spectrum of the white noise.

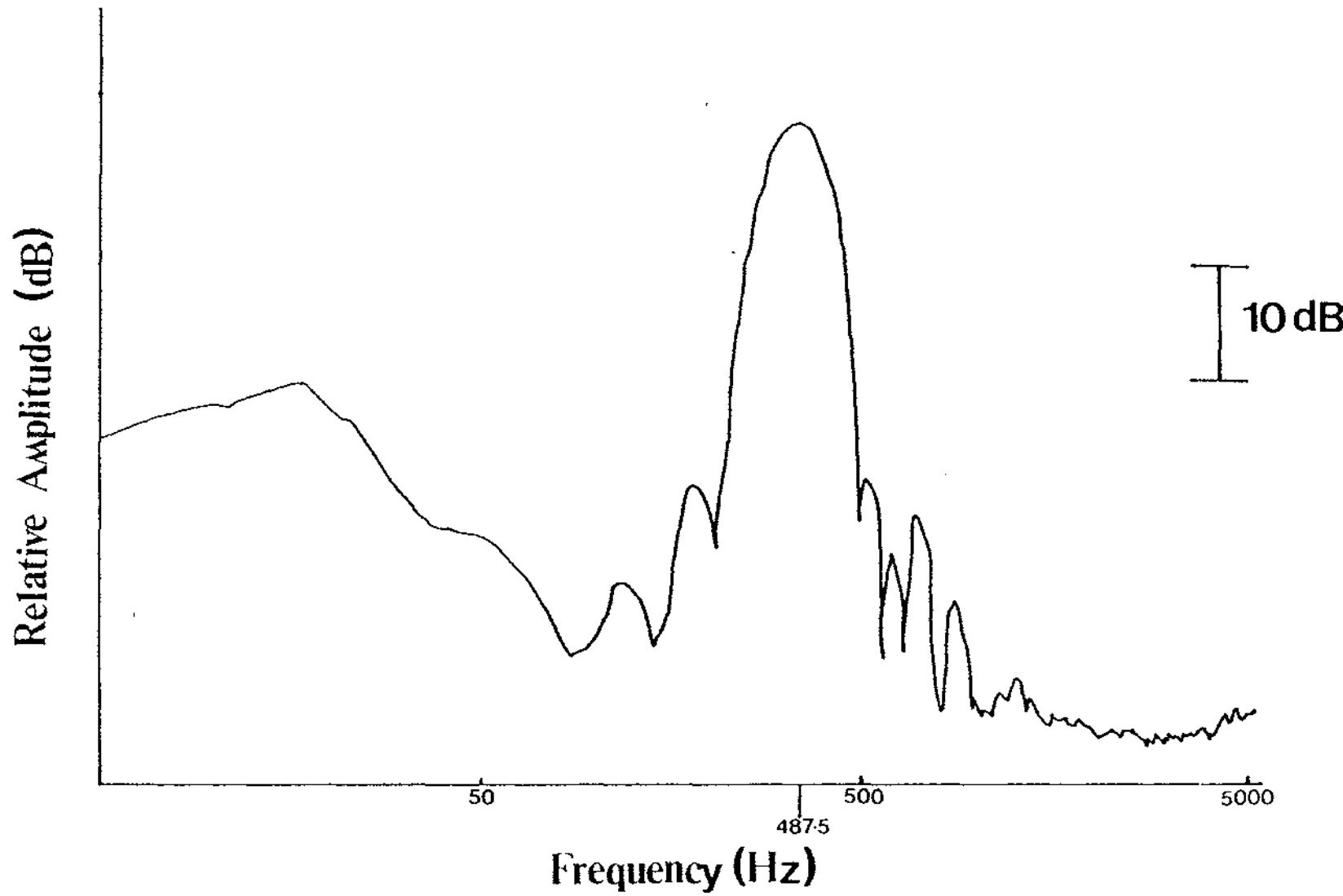


Figure 6. Acoustic spectrum of a 500Hz tonepip with 4 ms linear rise/fall times and a 2 ms plateau.

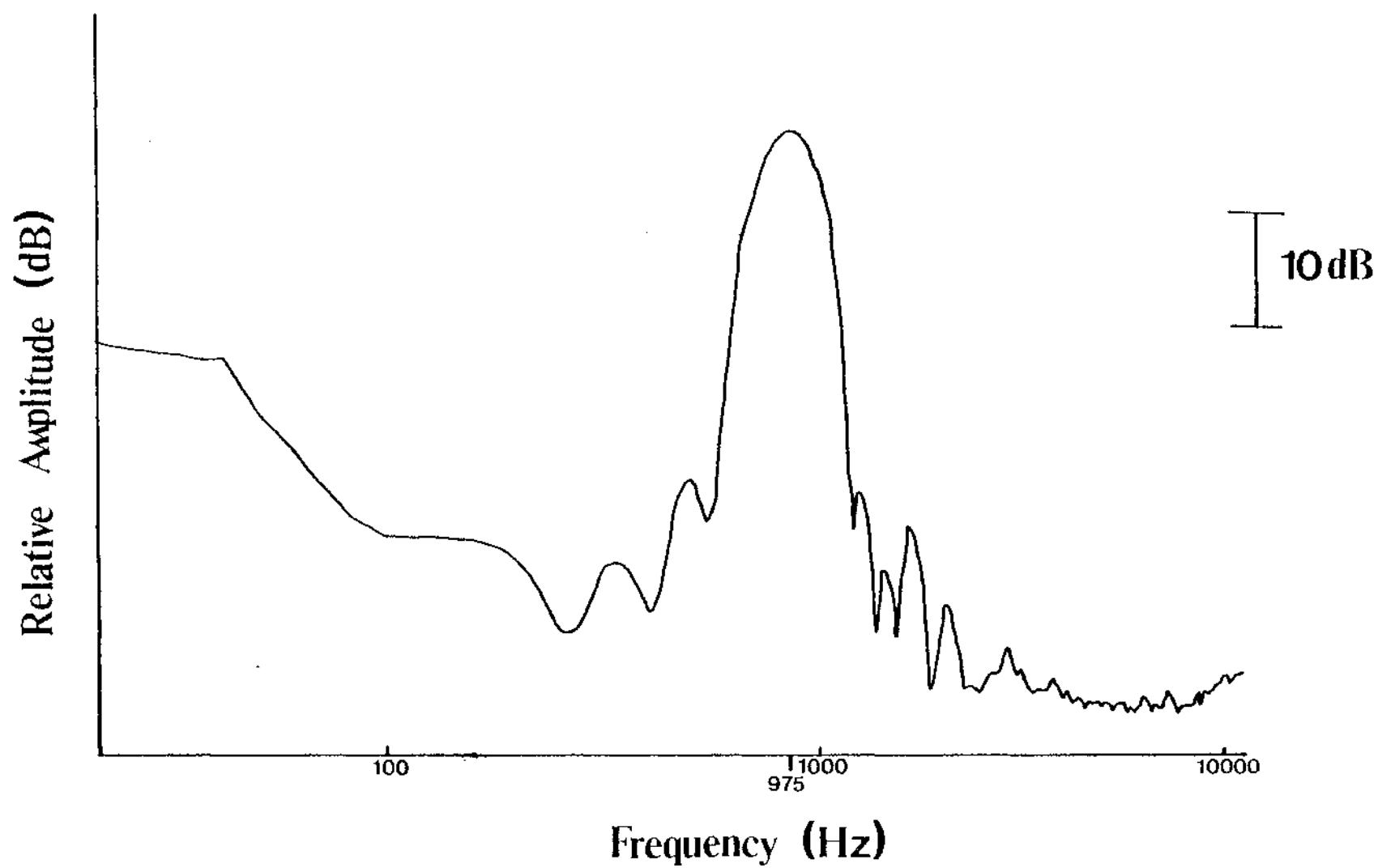


Figure 7. Acoustic spectrum of a 1000 Hz tonepip with 2 ms linear rise/fall times and a 1 ms plateau.

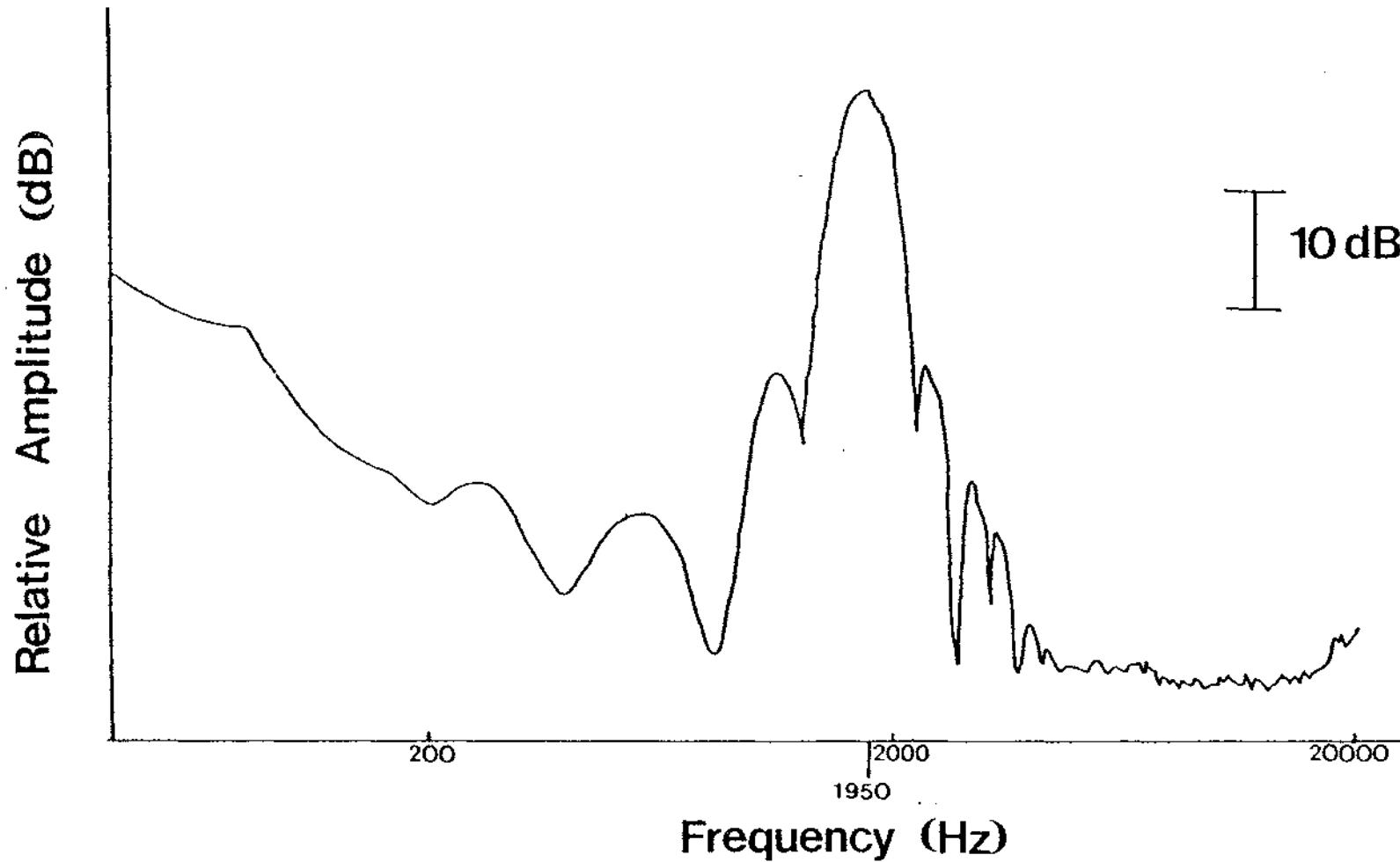


Figure 8. Acoustic spectrum of a 2000 Hz tonepip with 1 ms rise/fall and plateau times.

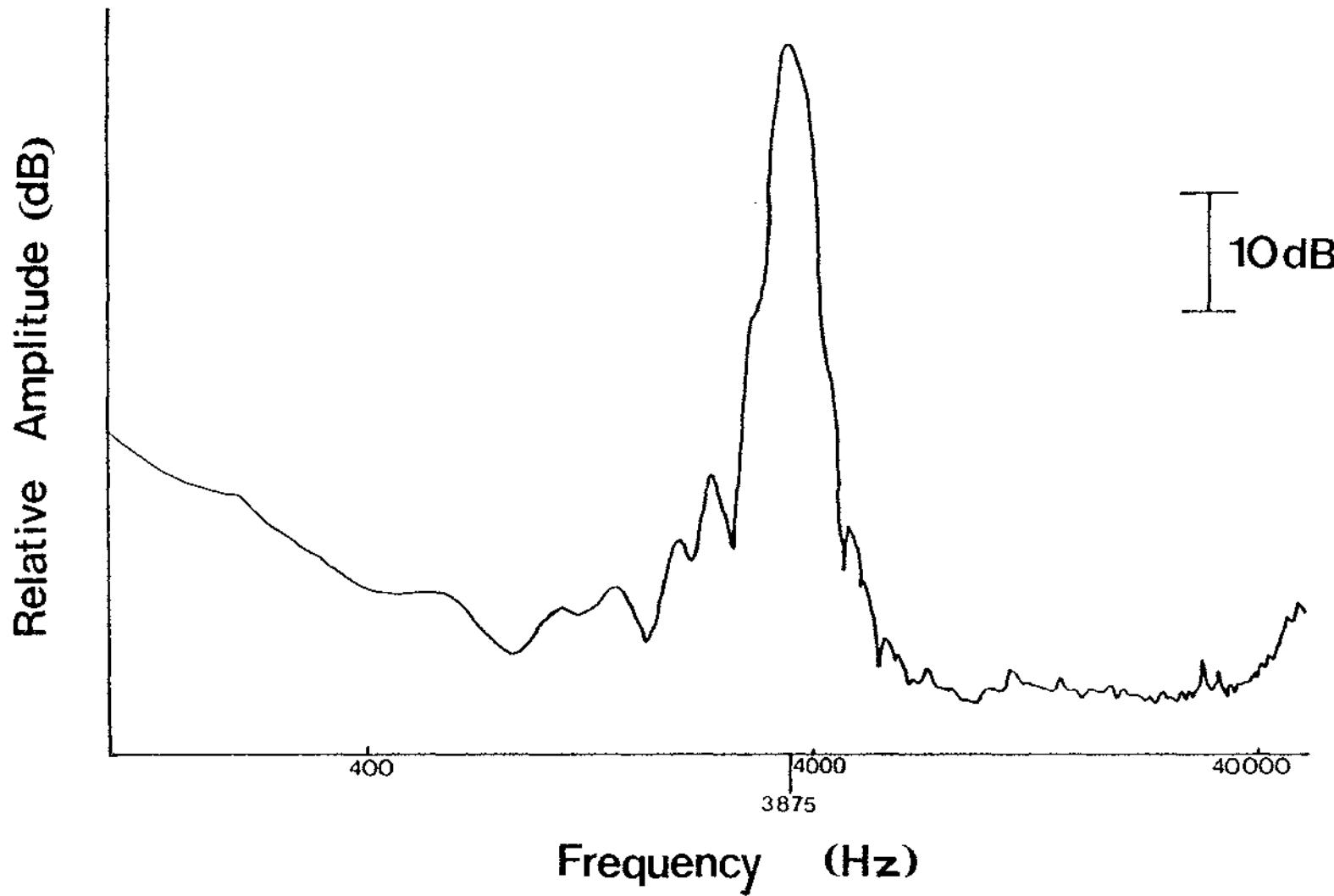


Figure 9. Acoustic spectrum of a 4000 Hz tonepip with 1 ms rise/fall and plateau times.

the limitations of the equipment at this frequency resulting in a longer rise/fall time in terms of the number of cycles, than for the other three frequencies.

The characteristics of the surface potentials filter is shown in Figure 10 demonstrating the 12 dB/octave roll-off above and below the cut-off filter settings.

Temporal waveforms of the tonepips were displayed on a Tektronix 7613 oscilloscope and photographed. These are shown in Figures 11 and 12 . For the 500 and 1000 Hz tonepips (Figure 11) the number of period(s) in the rise/fall and plateau is constant across frequency but duration varies. In contrast, for the 2000 and 4000 Hz tonepips (Figure 12) duration is constant though the number of periods varies. The spectra of the white noise and tonepips were measured across the TDH-49 earphone using a Brüel & Kjaer 2215 sound level meter and a Hewlett Packard 3581A wave analyser (30 Hz bandwidth).

PROCEDURE

The experiment was divided into three sessions:

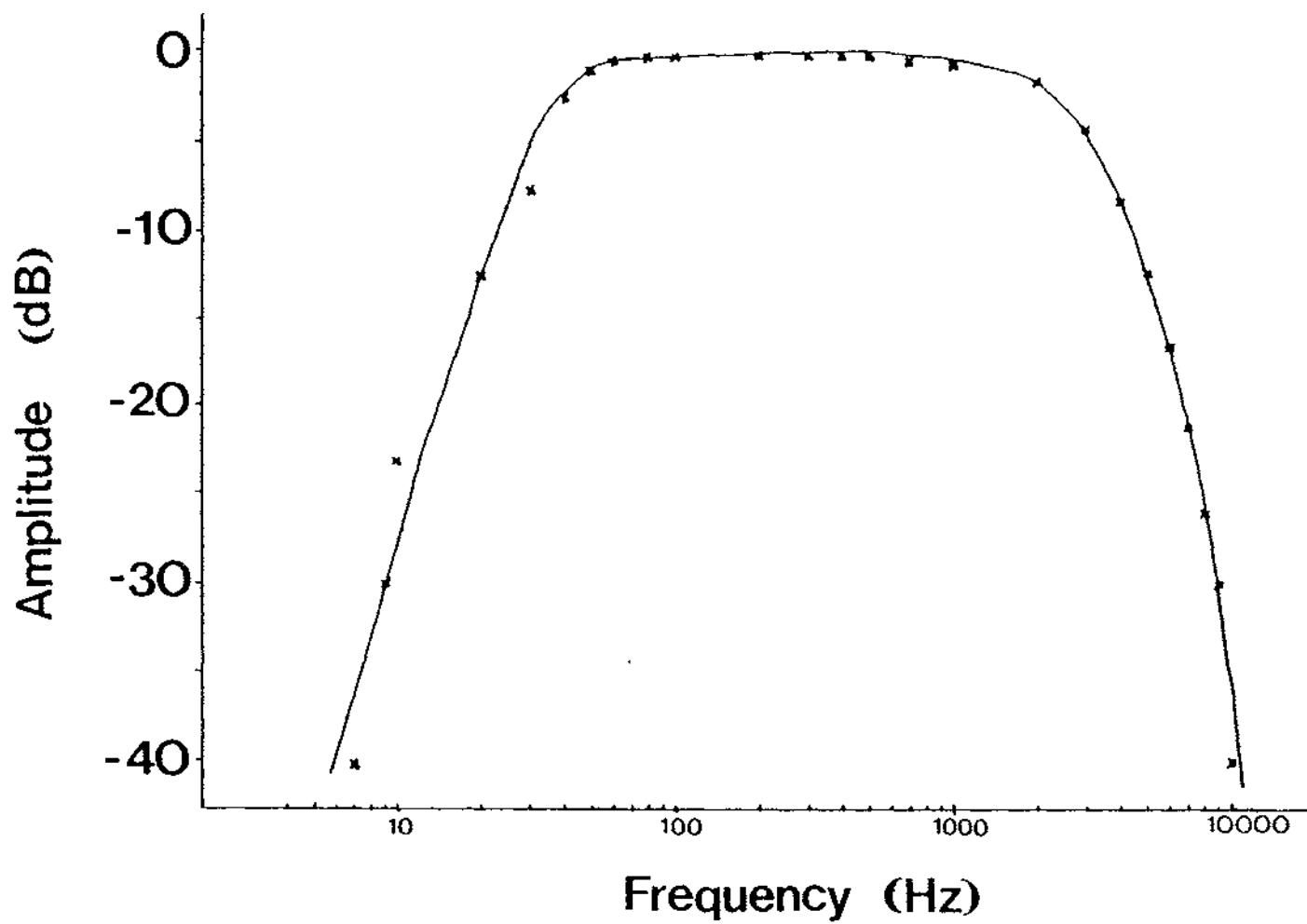


Figure 10. Characteristics of the surface potentials bandpass filter
(30–3000 Hz, 12dB/octave)

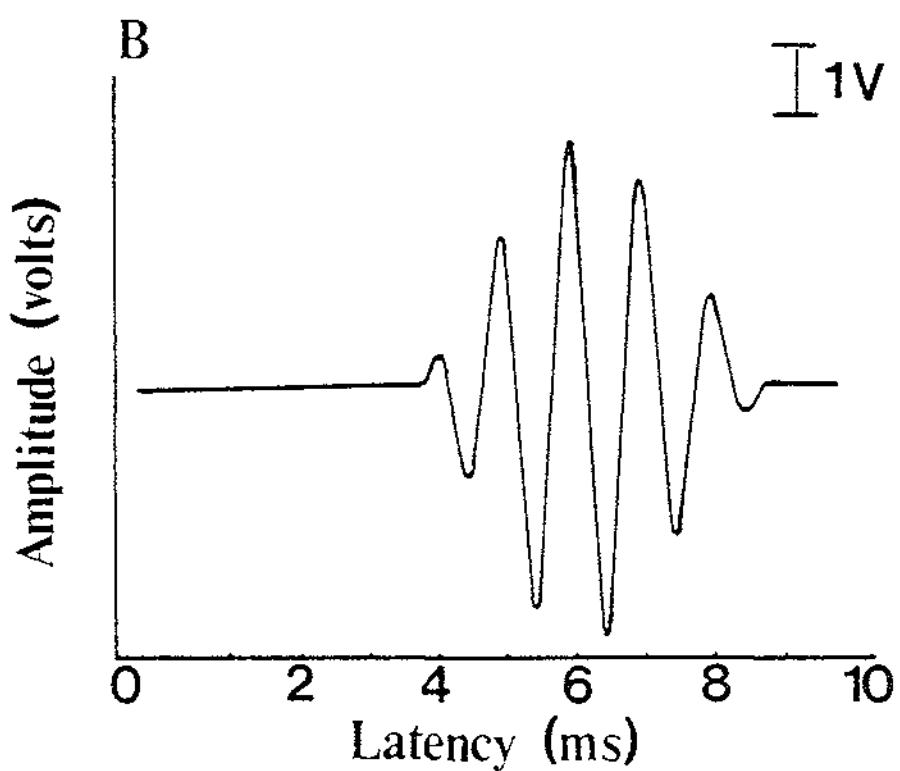
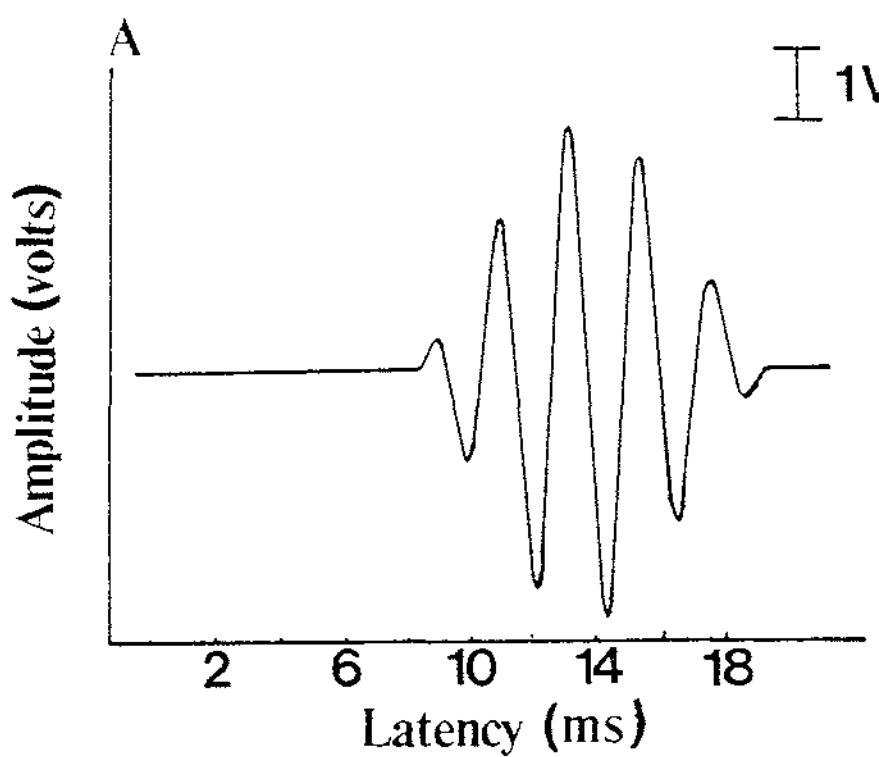


Figure 11. Temporal waveforms of (A) 500 Hz and (B) 1000 Hz tonepips.

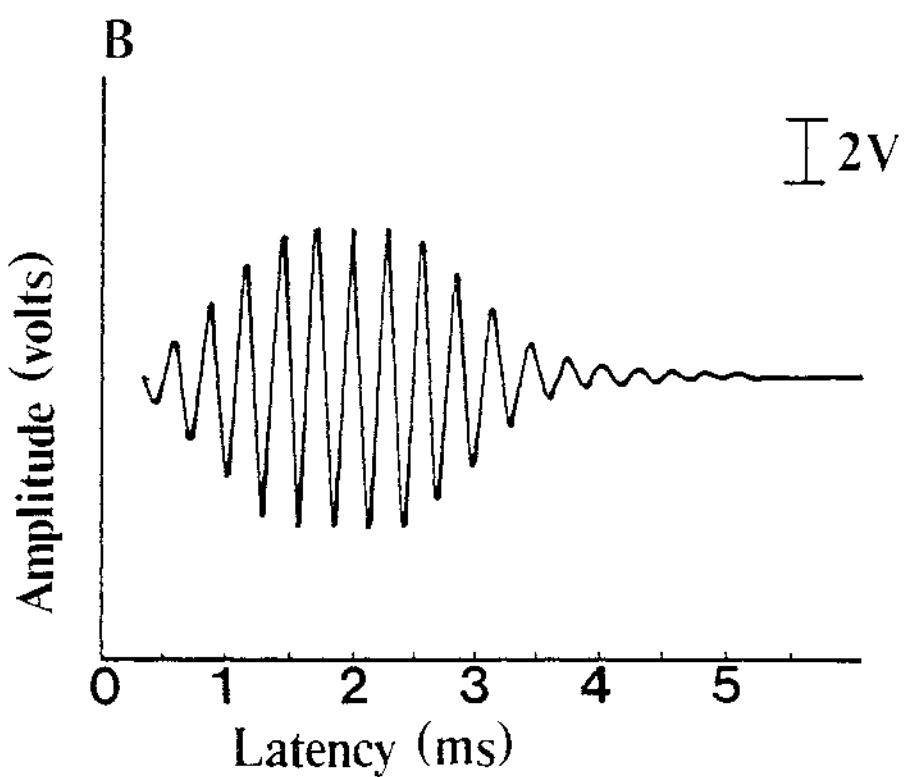
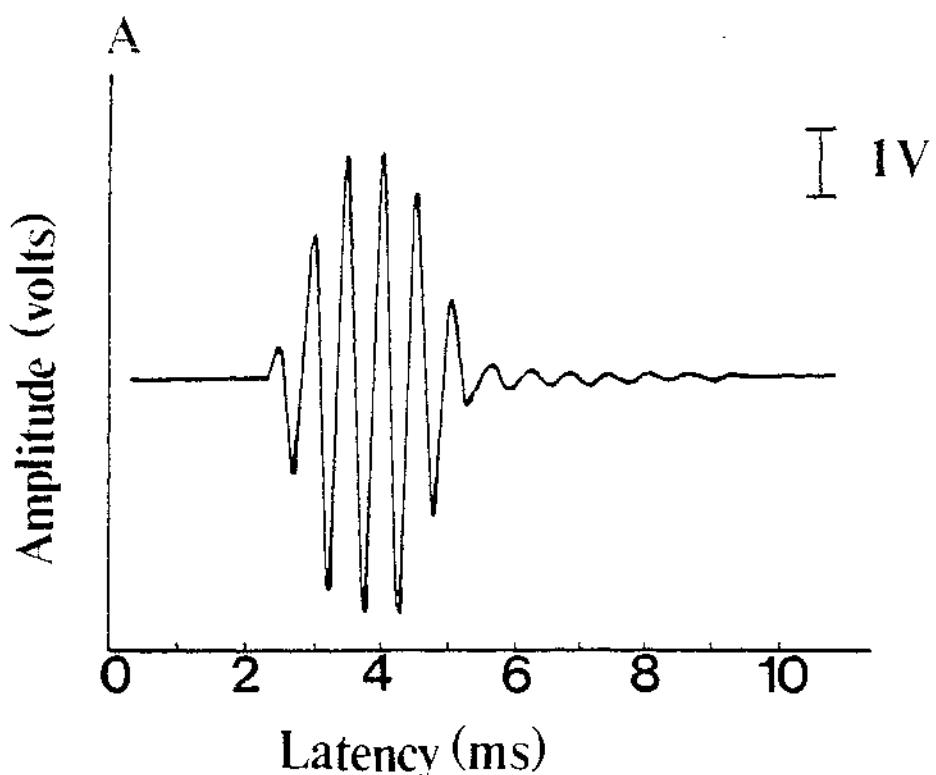


Figure 12. Temporal waveforms of (A) 2000 Hz and (B) 4000 Hz tonepips.

Session 1

A pure-tone audiogram was obtained for each subject (re ANSI S3.21-1978) to establish normal hearing. Although only the right ear was to be used for further testing, both ears were tested to ensure overall integrity of the subject's peripheral hearing.

Behavioural calibration of tonepips at each of the four test frequencies (500, 1000, 2000, 4000 Hz) was done to find the mean perceptual thresholds (corresponding to 0 dB nHL) for the 10 subjects. The subject was seated in a comfortable chair in the sound-attenuated room. Stimulus repetition rate was set to permit presentation of a single tonepip in each observation interval. Tonepips were presented to the right ear, beginning at a supra-threshold intensity and decreasing in 10 dB steps after a correct response. The subject was instructed to say "yes" each time a tonepip was heard. Responses were monitored by means of an Altai ETL 8083 intercom. When the subject failed to respond to the stimulus, intensity was increased in 2 dB steps with four stimulus presentations at each intensity, until three out of four stimuli were correctly detected at the same intensity. The intensity was then reduced by 2 dB and the ascending trials continued until the above criterion was met at two out of three presentations of the same intensity. The dial reading corresponding to this intensity was recorded and averaged

over all subjects. Stimuli were switched on and off manually at varying interstimulus intervals to provide random presentation.

An initial ABR measurement to broadband (100 microseconds, negative polarity) clicks was recorded as a check on the integrity of the brainstem response. Two recordings of 2000 clicks each were made on the right ear, at an intensity of 95 dB peSPL and a repetition rate of 41.7/second. A forehead/earlobe electrode configuration was used (forehead positive, right earlobe negative, left earlobe ground). The input sensitivity was set at \pm 10 microvolts. The EEG was bandpass filtered at 150 - 3000 Hz.

Session 2

Effective masking levels for tonepips in white noise were established behaviourally, using a procedure based on Campbell's (1963) block up and down, two-interval, forced choice (BUDTIF) method, a variation of the two alternative forced choice procedure. Tonepips at 500, 1000, 2000 and 4000 Hz were presented in random order at their respective rise/fall and plateau times. Presentation was at a constant level of 85 dB peSPL.

Two conditions were tested. In the first, tonepip repetition rate was set at 1/second. That is, one tonepip of overall duration determined by its set rise/fall and plateau time, was presented within each one second observation interval. In the second condition, repetition rate was 41.7/second. In each condition, 12 blocks of 4 trials per frequency (a total of 48 trials per frequency) were presented. Each trial consisted of two 1-second observation intervals with a 1-second inter-stimulus interval, followed by a 1-second response interval. At each frequency, tonepips were presented randomly in either the first or second observation interval (with equal probability of being in either interval over all trials). The subject was required to say which interval (one or two) the tonepip was present in. A light, switched on for the duration of each observation interval, indicated these intervals to the subject. Presentation of the tonepips was to the right ear only. The order of frequency presentation was randomised.

White noise was continuously presented to the right ear, the intensity of which was varied according to the following rules.

For each block of 4 trials:

If the subject scored >3 correct, intensity was increased by one step at the beginning of the next block of four trials.

If the subject scored 3 correct, intensity remained the same for the next block.

If the subject scored <3 correct, intensity was decreased by one step at the beginning of the next block.

In block one, the intensity of the noise was set at a level that ensured detection of the tonepips. At the beginning of each block, the noise was increased initially in steps of 10 dB, until the first reversal in intensity occurred (where <3 correct was scored). Thereafter, the intensity of the noise was changed in steps of 5 dB. Masked threshold (the level of noise that effectively masked the tonepips) was found by averaging all intensities presented more than once by the above method. Irwin (1984) has shown that this threshold-seeking method finds the 73% correct detection point.

Session 3

Effective masking levels for tonepips in white noise were established electrophysiologically. The subject, seated in the sound attenuated room, was prepared in the same way as for the ABR measurement in session 1. In this session a vertex/earlobe configuration was used with the positive

electrode being attached to the vertex to maximize wave V amplitude (Beattie et al., 1986). The subject was instructed to relax and encouraged to sleep if possible.

An initial ABR to tonepips was recorded at each of the four frequencies, 500, 1000, 2000 and 4000 Hz. Frequency order was randomized. Two runs of 1000 repetitions were recorded for each frequency, at a repetition rate of 41.7/second and a constant presentation level of 85 dB peSPL. Input sensitivity was set at ± 25 microvolts.

A clear, repeatable wave V was recorded at each frequency, and the latency at the peak of the wave measured. For peak identification, the maximum positive peak before a negative trough, with latency between 6 and 25 ms (the latter value being the maximum of the time window) was taken as wave V. If the peak formed a plateau, the latency was taken at the centre of the plateau (Stapells and Picton, 1981).

For each frequency, masking was then introduced, initially at an intensity low enough for a clear response to be recorded. To establish the masked threshold the level of white noise was increased in 10 dB steps (by adjusting the attenuator) until there appeared to be no repeatable waveform. Two runs of 1000 repetitions each were recorded at each masking level. The ABR was recorded with the masking noise set 5 dB above and 5 dB below the presumed masked threshold (that is, the level at which no

repeatable response was obtained). A "baseline" recording with white noise only (tonepips switched off) was also made to confirm the presence or absence of the response. If there was any doubt as to the presence of a response at any stage during the 10 dB step increase in masking, recordings were also made at 5 dB intervals. On occasion, a third recording was made at a given intensity if the response seemed ambiguous or the subject's response state altered while recording.

Subjects were given rest periods during the session to relieve discomfort from the headphones and help them to relax. Recordings were restricted as much as possible to periods in which subjects slept, since optimization of the ABR occurred when subjects were in this state.

Three of the 10 subjects were retested in a later session due to inability to relax sufficiently for a complete test during the third session.

All recordings were plotted and shown to three independent judges, experienced in reading ABR traces. Judges were required to make a "yes", "no" or "questionable" decision as to whether a response was present. Although identification of the ABR response by this method is subjective, it was the only practical means available and is a generally accepted procedure. For example, Hayes and Jerger (1982) used two judges experienced in evaluation of ABR response records to determine unmasked

ABR thresholds to tonepips at 500 and 2000 Hz. Responses were considered present only if both judges independently scored the record as positive for a response. Similarly, Beattie and Boyd (1985) and Folsom (1985) used independent judges to evaluate ABR waveforms. In the present study it was considered desirable to use three independent judges to improve inter-rater reliability.

Judges were given the following decision guidelines. (Guidelines were based on results from studies by Stapells and Picton (1981) and Beattie and Boyd (1985) on the technical aspects of brainstem evoked potential audiometry using tonepips.)

1. Waves must be clearly visible and replicable.
2. Wave V is identified as the maximum positive peak occurring between 6 and 18 ms after tone onset. If the peak is in the form of a plateau the latency is taken at the centre.
3. The maximum positive peak is followed by a negative trough. In the case of 500 Hz tonepips, this negative trough is the most prominent feature.
4. Amplitude decreases as masking intensity is increased.
5. Latency increases as masking intensity is increased, and frequency is decreased.

Recordings of the tonepip traces were shown to the judges in order of increasing masking level for each frequency, for each of the ten subjects. Subject order was randomized. Thus, the frequency and level of the masking noise was known to the judge. This was considered a more valid means of deciding on the presence or absence of a response, than making a "blind" decision, since the presence of amplitude and latency shifts with stimulus-intensity changes is of critical importance, and is widely used for clinical decision making. Each judge examined the traces in one session after data collection was completed.

Judges were instructed to respond with a "no" when they were definitely sure there was no response to the tonepip identifiable in the trace. If a response was definitely considered present, a "yes" was recorded. If the judge was not sure, a "questionable present" was recorded. Each judge independently scored the traces.

All judges' decisions were collated at each frequency for each of the ten subjects. For traces where there was not unanimous agreement among the judges, two "yes" and one "questionable" was accepted as a response present, while two "no" and one "questionable" was accepted as a response absent. The lowest masking value at which a response was recorded as absent, was accepted as the level where the

tonepip had been effectively masked, provided all judges had agreed there was "no" response when masking noise was presented at 5 dB above this level.

A total of 212 traces were shown to each judge. The judges made the same decisions for 191 of these, that is, total agreement was reached for 90% of ABR traces, indicating high inter-rater reliability.

Where a lack of agreement occurred, either two "questionable" and one "definite" decision was made at the same masking level, or a definite "yes" or "no" decision was given by one judge, at levels of masking noise different from that agreed on by the other two judges. Questionable decisions were evenly distributed across judges and tended to occur for particular subjects, for whom ABR recordings were more ambiguous.

Where disagreement occurred traces were again shown to the judges, who examined them together and discussed their decisions. Although high inter-rater reliability was achieved without this joint decision making, it was considered an interesting exercise to see if agreement could be improved, since clinically, subjective decisions of the presence of ABR responses often involve more than one clinician viewing and discussing results. Agreement was unanimous in 20 of the remaining 21 traces ,with a majority decision (two out of three) accepted for the last trace.

RESULTS

Session 1. Behavioural Calibration of Tonepip Thresholds

ABRs recorded to clicks showed clearly repeatable waves I, III and V at normal latencies (Greville, 1982) for each of the 10 subjects, indicating overall integrity of the brainstem response.

Thresholds resulting from the behavioural calibration of tonepips are shown in Table I. 0 dB nHL is defined as the mean dB peSPL values at each frequency. Behavioural thresholds were highly consistent across subjects, yielding relatively small standard deviations at each frequency of 1.8 to 3.5 dB. An analysis of variance showed a significant difference across frequencies ($F(3,39)=3.65$, $p=0.02$). A Tukey's Studentized Range (HSD) Test indicated that the threshold at 500 Hz was significantly higher than that at 2000 Hz ($q(0.05,36)=3.8$). Mean thresholds at 500 and 2000 Hz had the highest and lowest peSPL values respectively. Inter-frequency differences however are all less than 5 dB which is within the accepted clinical limits of test-retest reliability (Yantis, 1985).

Table I. Behavioural calibration of tonepips:

A single tonepip was presented at a rate of 1 every 2 seconds. Mean dB peSPL values equivalent to 0 dB nHL are shown.

<u>Subjects</u>	<u>Frequency (Hz)</u>			
	500	1000	2000	4000
1	38.0	31.0	29.0	31.0
2	34.0	31.0	29.0	33.0
3	32.0	29.0	27.0	31.0
4	32.0	29.0	27.0	31.0
5	34.0	33.0	31.0	31.0
6	34.0	33.0	31.0	27.0
7	34.0	33.0	33.0	33.0
8	34.0	29.0	29.0	35.0
9	38.0	33.0	31.0	29.0
10	34.0	31.0	39.0	39.0
Mean dB peSPL	34.4	31.2	30.6	32.0
Std. dev.	2.1	1.8	3.5	3.3

Session 2. Effective Masking Levels - Perceptual

Tables II and III show the levels of white noise required to effectively mask tonepips (established behaviourally). At each frequency the effective masking levels were averaged across the 10 subjects.

Table II shows effective masking levels for a single tonepip. One tonepip of rise/fall and plateau times as determined by the frequency, was presented in each one second observation interval. Total stimulus duration (plateau plus rise/fall times) for each frequency within the one second interval was as follows:

<u>Frequency (Hz)</u>	<u>Total Duration (ms)</u>
500	10
1000	5
2000	3
4000	3

Inter-subject differences were small with little variation in mean levels across frequencies. This was confirmed by the analysis of variance results which showed that effective masking levels for single tonepips did not differ across frequencies ($F(3,36)=0.85$, $p=0.5$). Standard deviations were comparable with those shown in Table 1 for the behavioural calibration of tonepips, the exception being at 2000 Hz, where the data showed greater variability.

Table II. Perceptual Masking:

Level of white noise (dB SPL) required to mask a single tonepip of 85 dB peSPL (presentation rate set at 1/second).

Subject	<u>Frequency (Hz)</u>			
	500	1000	2000	4000
1	93.7	85.7	78.7	86.7
2	81.7	85.7	86.7	86.7
3	84.7	88.7	74.7	86.7
4	84.7	84.7	95.7	83.7
5	87.7	81.7	73.7	87.7
6	86.7	86.7	83.7	83.7
7	90.7	78.7	89.7	86.7
8	86.7	86.7	82.7	85.7
9	83.7	85.7	81.7	81.7
10	81.7	82.7	85.7	84.7
Mean	86.2	84.7	83.3	85.4
Std.dev.	3.8	2.9	6.7	1.9

Table III. Perceptual Masking:

Level of white noise (dB SPL) required to mask tonepips of 85 dB peSPL at a presentation rate of 41.7/second (using a one second observation interval).

Subject	<u>Frequency (Hz)</u>			
	500	1000	2000	4000
1	97.7	87.7	88.7	92.7
2	93.7	90.7	89.7	89.7
3	95.7	96.7	92.7	87.7
4	90.7	92.7	92.7	90.7
5	93.7	91.7	91.7	88.7
6	96.7	92.7	87.7	87.7
7	86.7	88.7	88.7	87.7
8	93.7	89.7	85.7	87.7
9	93.7	84.7	84.7	87.7
10	91.7	94.7	90.7	88.7
Mean	93.4	91.0	89.3	88.9
Std.dev.	3.2	3.5	2.8	1.7

Table III shows effective masking levels for tonepips at a presentation rate of 41.7/second. This meant that for each one second observation interval, 42 tonepips were presented. It will be recalled that stimulus envelope characteristics were 4-2-4, 2-1-2, 1-1-1, 1-1-1 (rise-plateau-fall times in ms), for 500, 1000, 2000 and 4000 Hz respectively.

Total duration of the tonepip series for each frequency was as follows:

<u>Frequency (Hz)</u>	<u>Total Duration (ms)</u>
500	420
1000	210
2000	126
4000	126

High consistency is again evident across subjects, with standard deviations of 1.7 to 3.5 dB. A consistent trend across frequencies can be seen, with mean masking level increasing as frequency decreases. Mean effective masking levels at 500 and 4000 Hz differ by 4.5 dB. Thus, although there is a consistent trend in the data, all differences are within 5 dB. An overall significant difference was found for masking levels across frequencies ($F(3,36)=5.13$, $p=0.005$). A Tukey's Studentized Range (HSD) Test of the means indicated that the effective masking level at 500 Hz

was significantly higher than levels at 2000 and 4000 Hz ($q(0.05, 36)=3.8$). The masking level at 1000 Hz did not differ significantly from mean levels at any of the other three frequencies.

A comparison was made of the white noise masking levels for the two perceptual masking conditions (1/second and 41.7/second) to determine the effects of repetition rate. Masking levels for the 41.7/second presentation rate were consistently higher at each frequency than the masking levels for tonepips presented at 1/second. The average difference was 5.8 dB. A pairwise comparison of the mean masking levels at each frequency in Tables II and III indicated significant differences at all frequencies ($F(1, 18)=21.15$, $p=0.0002$ at 500 Hz; 19.19, $p=0.0004$ at 1000 Hz; 6.88, $p=0.02$ at 2000 Hz; 19.11, $p=0.0004$ at 4000 Hz).

Session 3. Effective Masking Levels (ABR)

The levels of white noise that obliterated the physiological response (ABR) to tonepips presented at 41.7/second are shown in Table IV. No significant effects due to frequency were found ($F(3, 36)=1.25$, $p=0.3$). These data show greater inter-subject variability compared to the perceptual masking levels, as evident from the higher standard deviations for ABR masking levels. Visual inspection of the mean effective masking levels suggests

Table IV. Physiological (ABR) Masking:

Level of white noise (dB SPL) required to mask tonepips of 85 dB peSPL at a presentation rate of 41.7/second.

<u>Subject</u>	<u>Frequency (Hz)</u>			
	500	1000	2000	4000
1	79.7	89.7	89.7	84.7
2	94.7	94.7	94.7	89.7
3	94.7	99.7	89.7	84.7
4	89.7	84.7	89.7	89.7
5	84.7	89.7	74.7	94.7
6	99.7	84.7	89.7	84.7
7	84.7	79.7	84.7	74.7
8	84.7	89.7	89.7	84.7
9	94.7	94.7	84.7	79.7
10	89.7	94.7	89.7	89.7
Mean	89.7	90.2	87.7	85.7
Std.dev.	6.2	5.9	5.4	5.7

a trend similar to that observed in the perceptual masking condition at 41.7/second (Table III). That is, effective masking levels increase with decreasing frequency. An inconsistency is noted at 500 Hz, however, where the masking level is 0.5 dB less than at 1000 Hz.

ABR masking levels and perceptual masking levels for the tonepip presentation rate of 41.7/second were compared. Pairwise comparisons of the mean masking levels (Tables III and IV) at each frequency showed no significant differences ($F(1,18)=2.8$, $p=0.1$ at 500 Hz: 0.13, $p=0.7$ at 1000 Hz: 0.7, $p=0.4$ at 2000 Hz: 2.92, $p=0.1$ at 4000 Hz). However, it is worth noting that mean perceptual masking levels shown in Table III at each frequency were consistently higher than ABR masking levels shown in Table IV, although none of the differences reached significance.

A similar pairwise comparison of ABR masking levels and perceptual masking levels at the 1/second presentation rate (Table II), was performed. Even though all perceptual levels were less than the ABR levels, the only significant difference was at 1000 Hz ($F(1,18)=2.29$, $p=0.1$ at 500 Hz: 6.83, $p=0.02$ at 1000 Hz: 2.63, $p=0.1$ at 2000 Hz: 0.03, $p=0.9$ at 4000 Hz).

Effective masking levels may also be expressed as signal-to-noise (S/N) ratios. This is a relative measure defined here as the difference in dB between the dB peSPL of the tonepip and overall dB SPL of the noise. Since the

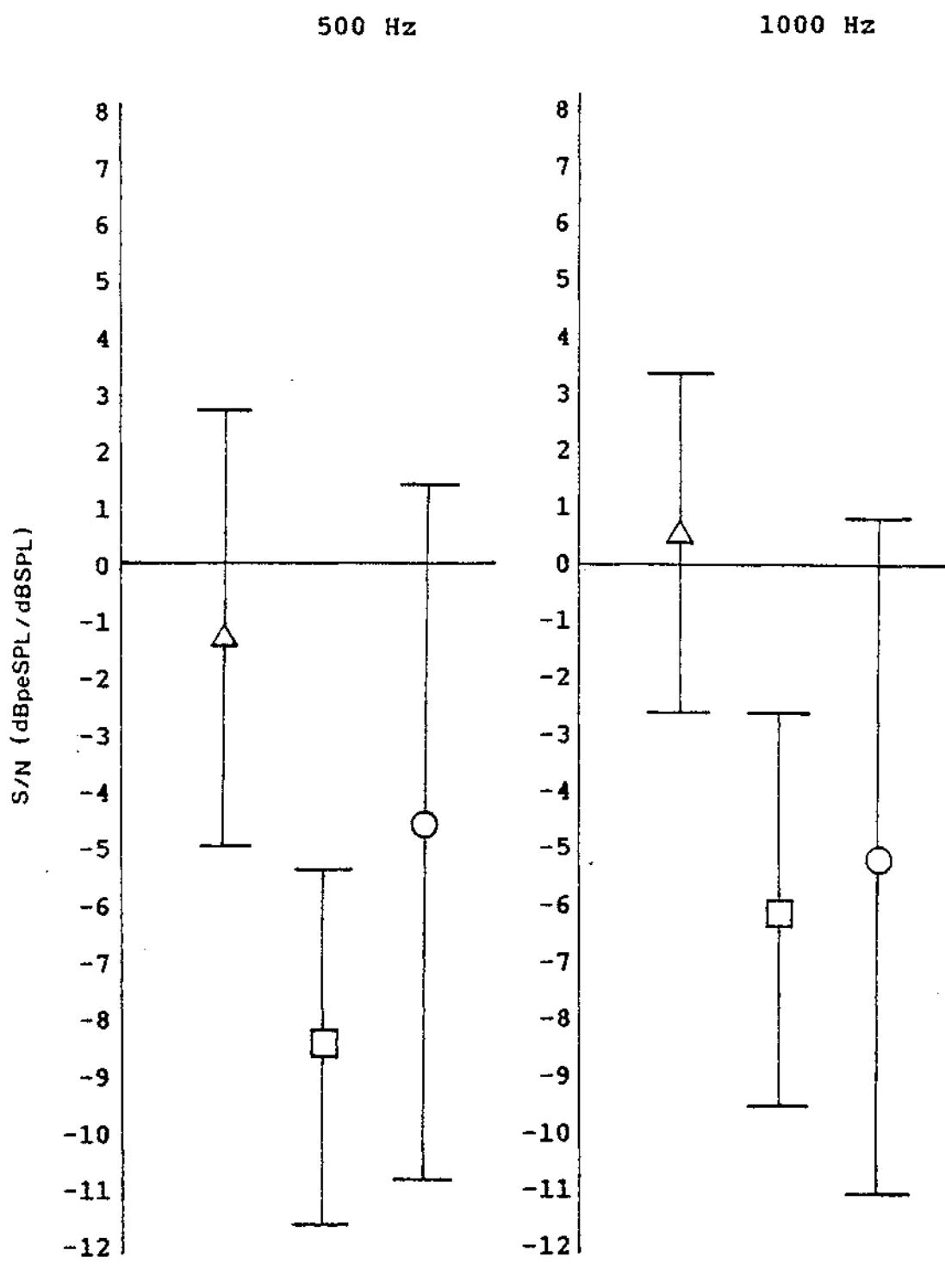
signal was presented at a constant level of 85 dB peSPL in the present study, the S/N ratio varied as a function of noise level. A larger S/N ratio indicates less noise was required to mask the signal. Mean levels of masking determined in each condition (perceptual masking at the two presentation rates, and physiological masking) are expressed as S/N ratios in Table V.

Graphical representations of these ratios are shown in Figures 13 and 14. These data show similar trends at each of the four frequencies. Mean S/N ratios are consistently larger for perceptual masking of single tonepips than masking of repeated tonepips (whether perceptual or physiological). That is, less noise was required for effective masking of single tonepips. However S/N ratios for masking of the ABR are consistently larger than levels for perceptual masking of repeated tonepips. Despite these trends, the only significant difference in the data occurred at 1000 Hz when comparing perceptual masking at 1/second to ABR masking.

A trend is also observed for the standard deviations. In general, standard deviations for the mean masking levels of the physiological response (ABR) are higher than for perceptual masking. The exception is for single tonepips at 2000 Hz. Standard deviations over all masking conditions range from 1.7 - 6.2 dB. Therefore, even though standard

Table V. Mean levels of effective white noise masking
 expressed as a signal-to-noise ratio (dB peSPL/dB SPL).
 The signal-to-noise ratio (S/N) is based on dB SPL
 white noise values shown in Tables II -IV. Standard
 deviations are shown in brackets.

<u>Masking Condition</u>	<u>Frequency (Hz)</u>			
	500	1000	2000	4000
Perceptual Masking 1/second	-1.2 (3.8)	0.3 (2.9)	1.7 (6.7)	-0.4 (1.9)
Perceptual Masking 41.7/second	-8.4 (3.16)	-6.1 (3.5)	-4.3 (2.8)	-3.9 (1.7)
Physiological Masking 41.7/second	-4.7 (6.2)	-5.2 (5.9)	-2.7 (5.4)	-0. (5.



—△— Perceptual Masking: 1/second
 —□— Perceptual Masking: 41.7/second
 —○— Physiological Masking: 41.7/second

Figure 13. Effective levels of white noise masking expressed as signal-to-noise ratios, showing mean S/N and 1 standard deviation bands.

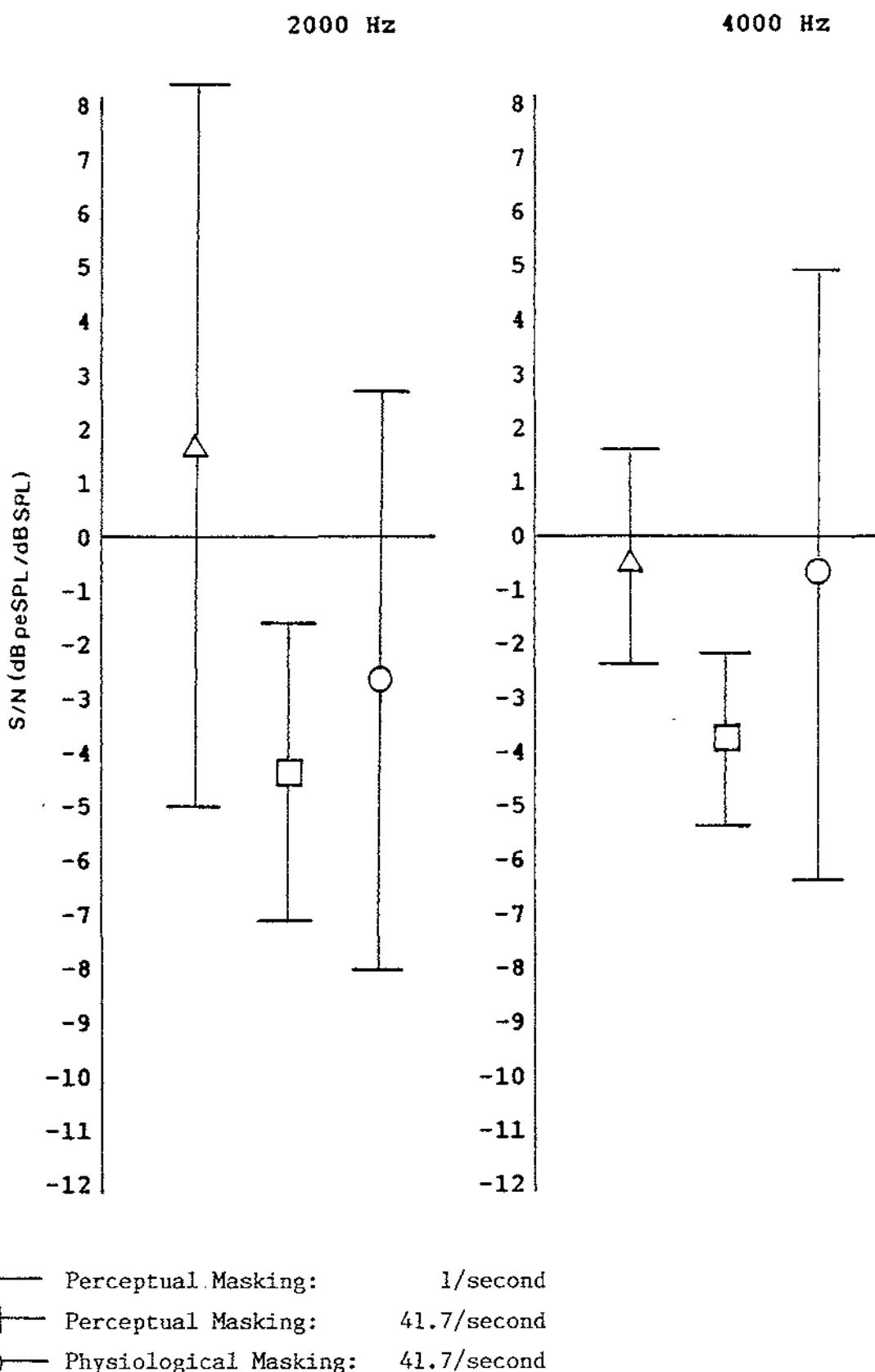


Figure 14. Effective levels of white noise masking expressed as signal-to-noise ratios, showing mean S/N and 1 standard deviation bands.

deviations are higher for ABR masking levels, these are only marginally higher than the accepted test-retest error of 5 dB.

Table VI shows mean latencies for wave V of the unmasked tonepip ABRs recorded from each subject. Consistency across subjects is evident from the very small standard deviations. Stapells (personal communication, January, 1986) points out that high variation in the peak latency of the response (especially at 500 Hz) precludes exact determination of latency. However the data in Figure 15, based on estimates of wave V latency at each frequency, show a definite trend of decreasing latency with increasing frequency.

Figure 16 shows a typical example of unmasked tonepip ABRs at the frequencies 500, 1000, 2000 and 4000 Hz recorded on a subject (DH) in the present study. Arrows indicate estimated wave V latency and illustrate the trend shown in Figure 15.

Table VI. Mean latencies and standard deviations
of the unmasked ABR wave V for 2-1-2 tonepips of
85 dB peSPL at a presentation rate of 41.7/second.

<u>Subject</u>	<u>Frequency (Hz)</u>			
	500	1000	2000	4000
1	10.1	7.5	6.9	7.0
2	10.6	8.3	7.2	6.9
3	8.1	6.8	6.5	6.6
4	8.9	7.8	7.1	6.2
5	7.9	8.1	5.3	6.5
6	10.5	8.2	6.5	6.8
7	8.4	6.8	8.0	6.1
8	9.7	7.4	7.0	7.2
9	10.3	8.4	7.5	6.9
10	10.0	7.5	6.5	6.7
Mean	9.5	7.7	6.9	6.7
Std.dev.	1.0	0.6	0.7	0.4

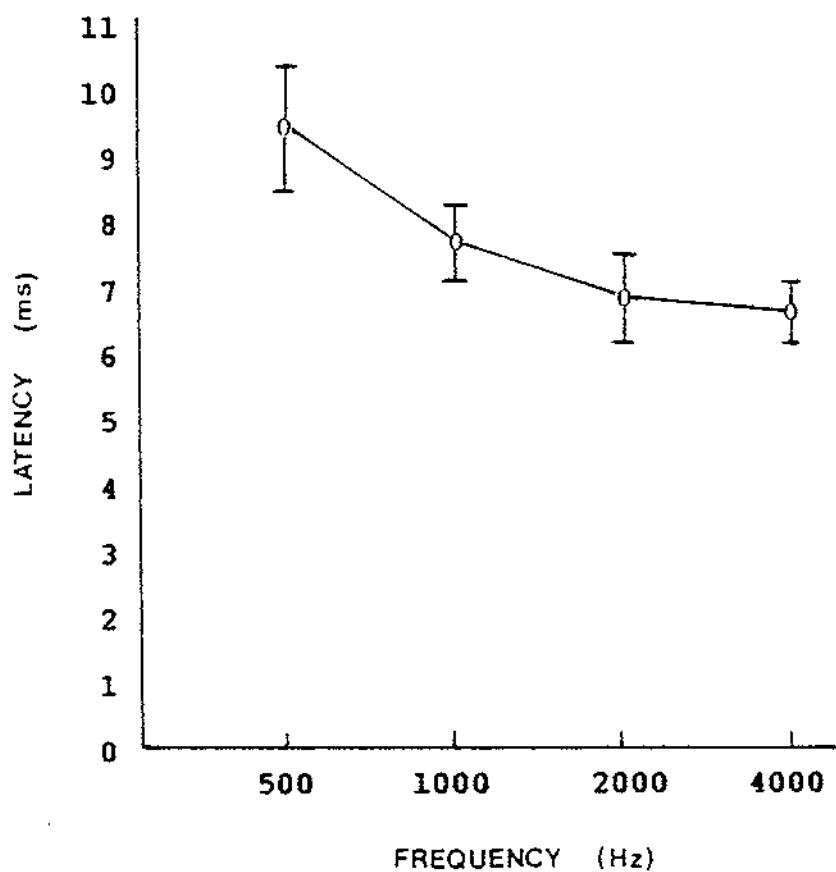


Figure 15. Mean latencies of wave V for unmasked tonepip ABRs to 2-1-2 tonepips. One standard deviation bands about the means are also shown.

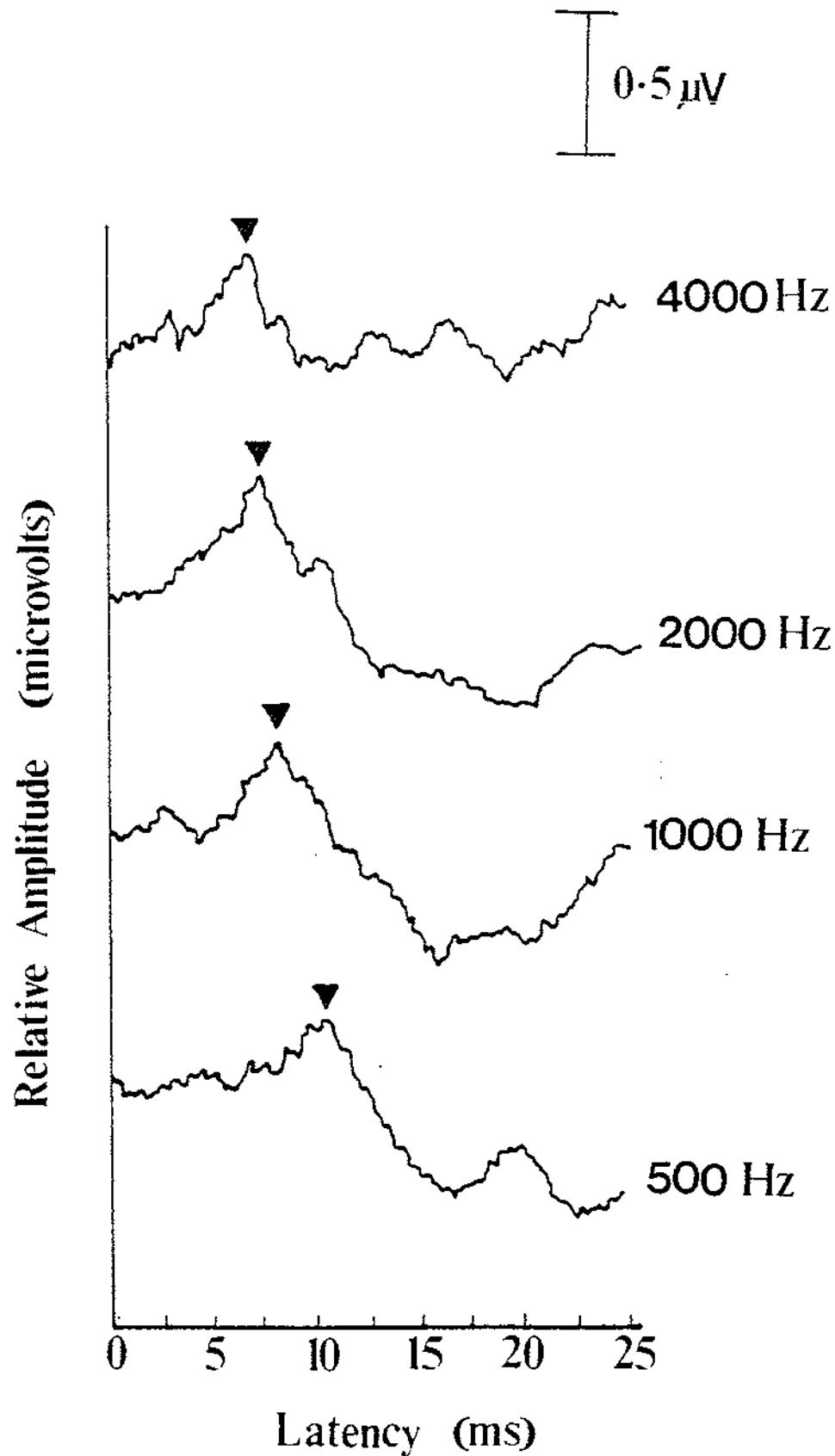


Figure 16. Unmasked tonepip ABRs recorded on a subject (DH) in the present study.
Arrows indicate wave V.

DISCUSSION

The results show that effective masking levels established behaviourally for single tonepips are significantly higher than those established behaviourally for repeated tonepips. Levels of effective masking of the ABR (physiological response) differed significantly at only one frequency when compared to both perceptual masking conditions. Consistent trends were evident, however, with most masking required for perceptual responses to repeated tonepips. Less masking was required for the ABR, followed by perceptual responses to single tonepips which required least masking.

The behavioural calibration of tonepips summarized in Table 1 shows a mean value of 32 dB across frequencies. This value represents 0 dB nHL for the group of 10 subjects in the present study. A significant difference was found between thresholds at 500 Hz and 2000 Hz, although this was within the accepted limits of test-retest reliability. Behavioural calibration in this study was based on the presentation of a single tonepip. Since ABR thresholds commonly use a behavioural nHL reference, it is of interest to investigate whether thresholds for tonepip stimuli are affected by stimulus repetition rate.

A study by Purdy (1986) using the same equipment and stimuli as the present study established behavioural thresholds for tonepips presented at a rate of 41.7/second

(so that 42 tonepips were presented in each observation interval). Davis et al. (1984) and Picton et al. (1979) also cite thresholds based on the behavioural calibration of tonepips at a high repetition rate (40/second). The results of these three studies in addition to mean thresholds found in the present study are summarized in Table VII.

Table VII. Behavioural calibration of tonepips:

Mean thresholds (dB peSPL) established
in four independent studies.

<u>Study</u>	<u>Frequency (Hz)</u>			
	500	1000	2000	4000
Present study	34.4	31.2	30.6	32.0
*2-1-2 tonepips; 1/s				
Purdy (1986)	27.6	23.0	22.0	22.8
*2-1-2 tonepips; 41.7/s				
Davis et al. (1984)	18.4	17.3	20.0	23.0
2-1-2 tonepips; 40/s				
Picton et al. (1979)	44.0	34.0	31.0	29.0
3 ms tonepips; 40/s				

* Subject to equipment limitations (Appendix 1(B))

Comparing behavioural thresholds reported by Purdy to those obtained in the present study, calibration at the faster presentation rate of 41.7/second resulted in thresholds 8.2 dB lower on average than for presentation of single tonepips.

These results indicate that behavioural thresholds for tonepip stimuli are dependent on repetition rate (that is, total stimulus duration) and may lead to different estimates of 0 dB nHL. This finding is consistent with results obtained by Picton et al. (1979) in which behavioural thresholds for tonepips (3 ms duration) presented at a rate of 40/second were 5.3 dB less on average than thresholds for the same stimuli presented at 1/second. Comparison of thresholds obtained in the present study with those of Purdy supports the suggestion of Picton et al. that changes in threshold with different stimulus presentation rates reflect temporal integration processes occurring when tonepips are repeated within the integration time of 200 ms and that rate of presentation must be considered when assessing behavioural thresholds.

Thresholds obtained by Purdy at 41.7/second agree well with those of Davis et al. at 40/second, being within 5 - 6 dB at all frequencies except 500 Hz, where there is a 10 dB discrepancy. Since the stimulus rise/fall and plateau times were exactly the same at 500 Hz in both studies, it must be

assumed that the difference in thresholds at 500 Hz is due to procedural and calibration differences in the respective studies.

In Davis et al.'s study, thresholds were established using a method of limits similar to that used by Purdy, and in the present study. Calibration of stimulus intensity, however, differed slightly in that Davis measured the root mean square (rms) SPL of the sinusoid that was modulated to form the tonepips, and took this value as the dB peSPL of the tonepips. An addition of 3 dB is required to convert rms to peak SPL for a sinusoid. If this amount is added to Davis et al.'s results in Table VII (which makes the calibration procedure equivalent to that used in both the present and Purdy's study), the difference between the corrected threshold at 500 Hz and that of Purdy's is reduced from 10 dB to 6.2 dB. Differences at the other three frequencies are within 5 dB. Correcting for differences in calibration procedures used in the two studies, therefore, yields closer agreement.

Behavioural thresholds obtained in Picton et al.'s study are considerably higher than those obtained by Purdy (14.8 dB on average), the greatest difference of 16.4 dB being at 500 Hz. It is difficult to determine why there is such a large discrepancy between these results. The discrepancy at 500 Hz can be partly accounted for by the difference in stimulus duration. Total stimulus duration within each observation interval in Purdy's study

was 420 ms. Unfortunately Picton et al. do not specify the duration of the observation interval used in their calibration procedure. However, if it is assumed to have been 1 second (comparable to Purdy's) then using a 3 ms stimulus at a repetition rate of 40/second, total stimulus duration would have been 120 ms. Temporal summation would account for a lower behavioural threshold for the longer duration (that is, faster repetition) stimulus, as used by Purdy.

The explanation of these results based on temporal integration effects assumes that rapidly pulsing tones within a brief time period will produce similar summation effects to a continuous tone presented for the same listening period. While differences in spectra are evident when comparing continuous and repeated stimuli, the threshold intensity of a pure tone has been shown to decline both with increase in duration and with increase in repetition rate of the sound (Garner, 1947a). However, for a given tonal duration, the decline in threshold with increase in repetition rate is less than the associated increase in energy predicts. This has been explained in terms of the increase in the bandwidth of a periodically repeated tone.

Thus, temporal integration alone cannot account for such a large difference in the 500 Hz thresholds. Stapells, Picton and Smith (1982) found the decrease in threshold

with increasing stimulus duration of clicks presented at 40/second to be only 2.5 dB per threefold change (100 to 300 ms) in the listening period. When rate was varied between 5 and 80/second, a decrease in threshold of 4.5 dB per tenfold change in rate was recorded. Differences between the studies of Purdy and Picton et al. shown in Table VII are larger than would be predicted from either of these results.

Apart from the use of different duration stimuli, procedural differences between Purdy's and Picton et al.'s study are difficult to establish. The latter study used an ascending method of limits with a minimum step size of 5 dB. Although stimulus intensity was calibrated using a 6 cc coupler, this would not have produced significantly different levels from those calibrated using the Brüel & Kjaer 4153 artificial ear in Purdy's study (Brüel & Kjaer, 1977, published data show differences in the order of 1 dB at 500, 1000 and 2000 Hz, and 4 dB at 4000 Hz). It therefore seems that unspecified procedural differences account for the discrepancy between Picton et al.'s results and those reported by Purdy and Davis et al. An interesting observation was the similarity of thresholds in the present study to Picton et al.'s at all frequencies except 500 Hz. Given the differences in stimulus parameters and the close agreement between the data of Purdy and Picton et al. for a high repetition rate, this similarity is likely to be coincidental.

Temporal integration effects on behavioural thresholds to tonepip stimuli and the discrepancies noted in the comparative studies described above highlight the need to specify all procedural details, including calibration and stimulus parameters when using a behavioural reference. This is especially important in the case of ABR audiology where ABR thresholds (from which pure-tone audiometric thresholds are predicted) are routinely based on a nHL reference.

Unfortunately many studies which report close agreement between ABR and behavioural thresholds, omit important procedural details. For example, Mitchell and Clemis (1977), Suzuki et al. (1977), and Davis and Hirsh (1979), all report ABR thresholds for tonepip stimuli within 10-12 dB of perceptual thresholds. However, the procedure for determining perceptual thresholds and the repetition rate used were not reported in any of these studies.

Given the fact that behavioural thresholds vary according to the repetition rate used for calibration, the question is raised as to which rate is most appropriate when determining a behavioural reference for ABR thresholds. Some studies have reported the stimulus repetition rates used for nHL behavioural calibrations, ranging from 8/second to 25/second. For example, Stapells, Picton and Smith (1982) evaluated normal thresholds for tonepips, assessing the effects on these thresholds of various parameters including presentation rate, duration and rate

effects are reported above. All differences were within 5 dB. They also collated published threshold data and laboratory thresholds obtained by several of their colleagues. There was a range of approximately 10 dB in reported thresholds across nine studies for clicks and tonepips. Repetition rate varied from 8 to 25/second, the majority being 10/second. Stapells et al. recommend that nHL thresholds should be calibrated at one particular rate. Since a rate of 10/second is commonly used in recording diagnostic brainstem responses, they recommend that this rate should also be used for nHL calibrations.

In the present study it was decided to establish behavioural thresholds using single tonepips. The rationale for this was based on the evidence that the ABR is an onset response and is not affected by temporal integration. For example, Hecox, Squires and Galambos (1976), demonstrated that the latency and amplitude of the brainstem auditory response are established exclusively at the onset of the stimulus. Provided sufficient time is allowed for response recovery, stimulus duration and offset have no effects on the ABR. While decreases in threshold and increases in subjective loudness were observed for behavioural responses to long duration (30 ms) as opposed to short duration (0.5 ms) signals, no simple correlate of temporal integration in the wave V response was observed. Given the independence of the ABR from duration and temporal integration effects, logically it would seem appropriate to use a behavioural reference also relatively

independent of temporal integration effects. A single tonepip was therefore thought to provide the best behavioural correlate to the ABR stimulus. Purdy's (1986) behavioural calibration data for a 41.7/second repetition rate were chosen for comparative purposes because of the availability of other studies citing behavioural thresholds established at a comparable rate (40/second) and because the present study utilized a 41.7/second repetition rate for establishing ABR masking levels. Clearly, further research is required on this important issue, and on the basis of these findings, investigators should be encouraged to adopt a standard repetition rate.

One way to determine the appropriateness of a behavioural threshold for single or repeated stimuli would be to directly compare behavioural and ABR thresholds. However this was not within the scope of the present study. The main aim of the present study was to establish effective masking levels for the ABR, and to compare effective masking levels established behaviourally and electrophysiologically. The effect of using single or repeated tonepips to establish perceptual masking levels was also investigated, the results of which are pertinent to the use of a behavioural reference for ABR thresholds.

Effective Levels of White Noise Masking - Perceptual

No frequency effect was found when comparing levels of white noise masking required to mask a single tonepip in the perceptual masking condition. In contrast, at the faster presentation rate of 41.7/second, perceptual masking levels were significantly higher at 500 Hz than at 2000 and 4000 Hz. All differences however, were less than 5 dB. This result is consistent with temporal integration studies that demonstrate less efficient integration at higher frequencies (Gengel and Watson, 1971) since a smaller effect of increased repetition rate was obtained in the higher frequencies.

For clinical purposes, the use of masking is simplified if one can assume a constant S/N ratio across frequencies. Table V shows S/N ratios expressed as the difference between the dB peSPL of the tonepip and the dB SPL of the white noise. A negative S/N ratio indicates that the overall SPL of the white noise is greater than the peSPL of the tonepip. For the perceptual masking conditions, a S/N ratio of -5 dB (being the most conservative estimate) effectively masks a single tonepip at each frequency, assuming a 5 dB minimum intensity step size. For tonepips presented at 41.7/second a -5 dB S/N ratio was also effective at 2000 and 4000 Hz. At 500 and 1000 Hz, however, lower S/N ratios of -8.4 and -6.1 respectively, were required. In general, setting the overall SPL of the noise at 5 dB above the peSPL of the tonepip was found to

provide effective perceptual masking of tonepips at all frequencies for both conditions. The exceptions were 500 and 1000 Hz tonepips at a presentation rate of 41.7/second, where slightly higher levels of noise were required.

Stapells (personal communication, January, 1987) also established effective masking levels behaviourally for 2-1-2 tonepips at a 10/second repetition rate. S/N ratios given at 500, 1000, 2000 and 4000 Hz were -2.3, +2.1, +5.3 and +6.4 respectively. These ratios indicate effective masking levels are 6 to 10 dB lower than those found in the present study for masking levels established behaviourally to repeated tonepips. The trend is similar however, in that more noise was required to effectively mask the lower frequencies. A S/N ratio of -5 dB would encompass all of Stapells' data. The difference between Stapells' levels and those at the 41.7/second repetition rate in the present study may result from intensity and rate effects. Stapells determined effective masking levels at threshold and used a slower repetition rate (10/second).

When levels of white noise required to perceptually mask single tonepips in the present study were compared with levels required to perceptually mask repeated tonepips (41.7/second), masking levels for the repeated stimuli were significantly higher at all frequencies.

That is, more noise was required to mask the repeated tonepips. This finding is consistent with the effects of temporal summation. It has been shown

that for behavioural responses to tones, integration of acoustic energy occurs, resulting in a perceptually louder stimulus and hence lower thresholds for long-duration tones (Picton et al., 1979; Stapells, Picton and Smith, 1982). Given the higher levels of masking required for the repeated tonepips (at 41.7/second), it may be assumed that temporal integration resulted in perceptually louder stimuli in this condition, compared to single tonepips (at 1/second presentation). As a result, higher levels of white noise masking were required to effectively mask the tonepips. Averaged over all frequencies, levels of effective masking were 5.8 dB higher at the 41.7/second presentation rate. This equates to a 1.4 dB decrease in threshold per tenfold increase in rate/second. Although this is less than the 4.5 dB per tenfold increase in rate/second for unmasked clicks cited by Stapells, Picton and Smith (1982), it is consistent with Stapells et al.'s finding of a smaller summation effect for brief stimuli than the 8 - 10 dB per tenfold increase in duration commonly found for long duration pure tones (Plomp and Bouman, 1959).

The result from the present study agrees well with that of Picton et al. (1979) in which unmasked tonepip thresholds were 5.3 dB less at 40/second than at 1/second, corresponding to an approximate 1.3 dB decrease in threshold per tenfold increase in rate/second. In contrast, Davis et al.'s (1984) report of an absence of any significant rate effect is not supported by the present

study. Although non-significant, a consistent difference was noted by Davis et al. for repetition rates between 4 and 40/second.

Effective Levels of White Noise Masking - Physiological

Effective masking of the ABR to tonepips at all frequencies occurred when the overall SPL of the noise was 5 dB above the pesPL of the tonepip. This -5 dB S/N ratio was the same as that found effective for perceptual masking of single tonepips at all frequencies, and repeated tonepips at 2000 and 4000 Hz. At 500 and 1000 Hz, however, a S/N ratio of -10 dB is required to ensure effective masking. Although there was no significant difference in the pesPL masking levels when ABR levels were compared to perceptual levels at 41.7/second, the difference in S/N ratios at 500 and 1000 Hz should be considered for clinical purposes. Consequently a S/N ratio of -5 to -10 dB may be accepted as effective at all frequencies for both ABR and perceptual masking conditions. The more conservative estimate of -10 dB would encompass all the data.

It is difficult to equate electrophysiological and perceptual responses to tonepips because of differences in underlying mechanisms. However, based on our understanding of temporal integration effects one might have expected ABR masking levels (which are largely independent of stimulus duration) to differ from perceptual levels that show

greater evidence of temporal summation, in this case, levels established perceptually to tonepips at 41.7/second. Similarly, ABR masking levels might be expected to be more comparable to perceptual masking levels for single tonepips given less influence on both of temporal integration. Neurologically the ABR may be more similar to the perceptual response to single tonepips, since the ABR results from the averaging of the synchronized neural responses to each tonepip.

The results of the present study show no statistically significant difference in effective masking levels (with one exception at 1000 Hz for single tonepips) when ABR masking levels are compared to behavioural masking levels. Visual inspection of the data, however, show consistent trends in the differences between the ABR and perceptual masking levels, for both repeated and single tonepips. Although statistically insignificant these trends may indicate real differences in underlying processes. The results indicate that a behavioural method of establishing effective masking levels is acceptable for the stimulus and recording parameters used in the present study. This does not assume that physiological and behavioural methods are equivalent, since the underlying differences of neurological and psychophysical processes remain. For clinical purposes, the advantages of a behavioural method are ease of implementation and the requirement of shorter testing time than for physiological methods.

The results also indicate that standard deviations were generally lower in the perceptual masking conditions when compared to the ABR masking condition. Since the ABR was susceptible to changes in subject state, the effect of subject state on threshold may have introduced greater variability in the ABR data. Other studies have also shown that the tonepip ABR is affected by subject state (Beattie et al., 1984; Gorga et al., 1984). Less variability may have occurred if recordings had been restricted entirely to periods when the subject slept. The smaller variability in the perceptual threshold data may be one more factor in favour of the use of a behavioural method of establishing masking levels.

If a behavioural method is to be used, the question remains of which stimulus repetition rate is more appropriate. Overall, in the present study no statistical differences were evident when ABR levels were compared to perceptual levels at either rate (with one exception). Since a repetition rate of 41.7/second is routinely used for clinical ABR testing of infants, determination of effective masking levels at this rate for the perceptual masking of tonepipes seems appropriate. This contrasts with Stapells et al. (1982) recommendation of using a 10/second presentation rate for calibration of click stimuli for diagnostic purposes.

Although the results of the present study suggest effective levels of masking determined behaviourally for repeated stimuli may be used in ABR measurements, if the results are to be applied to other clinical settings, normative studies should be done to ensure validity within those settings. This applies also to establishing behavioural thresholds to provide a nHL reference for ABR thresholds. The large variation in reported estimates of 0 dB nHL and the effects of temporal integration associated with different repetition rates used in behavioural calibrations, also restrict the applicability of results to the clinical and research settings in which they have been determined. The use of a nHL behavioural reference for ABR measurement is appropriate provided the above restriction is acknowledged, and all stimulus parameters, calibration procedures and actual behavioural thresholds are stated, so that the exact relationship between ABR and behavioural thresholds is known.

Because of the problems associated with using a behavioural reference for ABR measurements, a calibration scheme based on physical characteristics of the stimulus has been recommended. For example, Gorga et al. (1984), while not advocating that behavioural threshold references be discarded, do suggest that a physical reference may simplify comparisons of data from different laboratories and clinics, leading to the development of a more cogent body of ABR data. This would avoid the extraneous effects introduced by processes such as temporal integration into

the interpretation of measurement of electrophysiological responses. Although this is advantageous, clinical limitations for calibrating stimuli often dictate the need for behavioural calibration.

While the problems associated with behavioural and electrophysiological comparisons need to be considered, the practice of audiology requires such comparative measures. Behavioural or psychoacoustic thresholds take advantage of the capabilities of the entire auditory system while the ABR essentially provides only a measure of peripheral and lower central function. The ABR has proved to be useful in the assessment of hearing sensitivity since behavioural audiograms may be predicted on the basis of ABR thresholds, for subjects who cannot be tested by conventional audiometry. For the clinician, audiometric thresholds represent the target or ideal. Valid procedural methods and correction factors must be sought to allow estimation of overall performance from electrophysiological tools such as the ABR.

Improvements to the present study may help to clarify the issue of behavioural versus physiological calibration of stimuli for use in ABR measurement.

Tonepips with equivalent rise/fall and plateau times in terms of the number of cycles at all frequencies would have added consistency to the parameters used in the present

study and would have allowed more direct comparison to other studies using 2-1-2 tonepip stimuli. Unfortunately, equipment limitations did not allow this.

To eliminate subject effects, perceptual thresholds to tonepips at a 41.7/second repetition rate could have been established for the same subjects in the present study to enable comparison with thresholds for single tonepips.

The S/N ratios effective in the present study were determined at only one stimulus presentation level. For application to other test situations, the constancy of these ratios at different stimulus intensity levels should be investigated.

The method of judging ABR recordings may have introduced confounding effects. The use of judges to determine the presence of a response introduces a subjective element into what is otherwise an objective measure of auditory function. Ideally, the use of more objective scoring methods such as the on-line computer detection technique advocated by Mason (1984) would be desirable. Because of equipment limitations these procedures are not available in most clinical settings. Instead, the use of at least two independent judges, experienced in evaluation and interpretation of recordings is most often reported (Hayes and Jerger, 1982; Beattie and Boyd, 1985). In the present study, three experienced judges were used to improve inter-rater reliability. Nevertheless, possible

confounding effects due to fatigue (all traces were scored in one sitting) and knowledge of stimulus conditions should be considered. Judges' decisions may have been biased due to the expectation of presence or absence of a response based on the level of masking. Attempts were made to ensure each judge maintained a constant criterion for making his/her decision, by giving explicit guidelines and instructions. It would be of interest to have all traces rated with judges blind to masking levels, and compare the decisions to those in the present study. Nevertheless, the knowledge of masking levels when making judgements was considered a more comparable procedure to clinical decision making.

Effective masking levels found in the present study were established for normal-hearing subjects. Clinical application, however, would primarily involve other populations, specifically hearing-impaired subjects and infants. The validity of these levels for use in the assessment of infants and when determining the degree of hearing impairment, needs to be considered.

Evidence suggests that subjects with cochlear damage may encode auditory stimuli differently from subjects with normal cochleas (McGee and Clemis, 1980). For example, subjects with cochlear hearing loss have poor frequency selectivity as evidenced by abnormal tuning on psychophysical tests. Evidence suggests that changes in underlying neurological processes occur for

subjects with cochlear loss, such as a reduction in sharpness of tuning curves to single auditory fibres, and elevation of threshold at the characteristic frequency (Gorga et al., 1983). Psychoacoustic studies have demonstrated that subjects with cochlear damage encode brief duration stimuli differently from persons with normal cochleas, as evidenced by less temporal integration (Gorga et al., 1984). These factors may alter the relationship between behavioural tonepip thresholds and audiometric thresholds, as determined on normal-hearing subjects. Thus the sensitivity of ABR measurements which use a behavioural reference may depend on the presence and degree of hearing loss. Further study into how hearing loss affects the relationship between behavioural and physiological measures is required.

Masking levels established in the present study should be validated on hearing-impaired subjects, to examine possible confounding effects of cochlear pathology. The effective masking levels established in the present study may be used when measuring masked tonepip ABR thresholds to determine the relationship between pure-tone audiometric thresholds and ABR thresholds in subjects with different degrees and configurations of hearing loss.

The primary application of results from the present study is to the assessment of infants using ABR audiology. The current use of click-evoked ABRs to assess hearing yields limited frequency-specific information. ABRs to masked

tonepips offer a more informative and accurate measurement, allowing assessment of hearing sensitivity at specific frequencies across the speech spectrum and enabling more accurate and efficient rehabilitative intervention.

The accuracy of frequency-specific thresholds depends on the masking effectiveness. Application of the masking levels obtained in the present study to infant assessment requires interpretation of infant responses based on adult norms. Many studies have demonstrated differences between adult and infant ABRs which may reflect a more immature peripheral hearing apparatus in the infant (Folsom, 1985). The effects of masking on the neonatal ABR have also been noted with lowpass and highpass maskers producing latency shifts and amplitude changes that differ from those seen in the equivalent masking of the adult ABR (Folsom, 1984; Klein, 1986). Masking profiles have demonstrated different frequency contributions to the infant ABR, showing greater contribution of low frequencies and less of high frequencies when compared to ABRs of adults (Hecox, 1975).

Given these differences it cannot be assumed that masking levels effective for adults are as effective for infants. Thus infant norms need to be established. While these can be determined electrophysiologically, behavioural assessment is a more difficult task, given the limited behavioural response repertoire available to the infant under 6 months of age (Kaga and Tanaka, 1980). Similarly, validation of tonepip ABRs as a measure of infant hearing

sensitivity requires a means of assessing how well overall auditory function can be predicted by ABR thresholds. To achieve this, ABR thresholds established in the neonate need to be compared to hearing measures when the infant is old enough to be reliably assessed behaviourally.

Summary

The results of the present study found that S/N ratios of -5 to -10 dB ensure effective masking of the ABR to tonepips. Effective masking levels were established behaviourally and physiologically. Only one statistically significant difference was found when ABR masking levels were compared with perceptual masking levels, although general trends in differences were evident. Perceptual masking levels were significantly different when established to single and repeated tonepips, consistent with temporal summation effects. The results suggest that behavioural determination of effective masking levels is acceptable, for the recording and stimulus parameters used in the present study. Application of these results to other settings requires further normative studies.

Effective masking levels established in the present study may be used to aid in the establishment of a more frequency-specific method to assess hearing sensitivity using the ABR. The S/N ratios found to be effective for normal-hearing subjects may be used for further investigation of the relationship between pure-tone audiometric thresholds and ABR thresholds to tonepips. Of paramount clinical importance is the application of these results to frequency-specific ABR measurement in infants. The use of tonepip stimuli in filtered noise at

an effective masking level has potential as a means to accurately establish hearing thresholds in subjects for whom reliable behavioural assessment is unobtainable.

APPENDIX 1

(A) Calibration of Clicks and Tonepips

The following describes calibration of stimuli generated by the Nicolet NIC 1002 stimulus generator and CA 1000 averager and measured through a Telephonics TDH49 earphone:

Equipment:

Bruel & Kjaer 2215 Sound Level Meter
Bruel & Kjaer 4134 Microphone
Bruel & Kjaer 4153 Artificial Ear
Bruel & Kjaer 4230 Calibrator
Krohn Hite 4100 Oscillator
Hitachi V-509 Oscilloscope

Peak Equivalent Sound Pressure Level (peSPL) of the click/tonepip was measured as follows:

The TDH-49 earphone was positioned on the artificial ear, attached to the sound level meter, and a 500 gram lead weight applied. The AC output of the sound level meter was routed to an oscilloscope and the peak-to-peak voltage of the click or tonepip waveform was measured. Then a continuous sinusoid, at the resonant frequency of the earphone, was routed through the earphone and its level adjusted to equal that of the stimulus peak-to-peak voltage. In the case of tonepip measurement, the stimulus unit was set to deliver tonepips at each of the four

frequencies, 500, 1000, 2000 and 4000 Hz with a 2 cycle rise/fall time and 1 cycle plateau time, at a rate of 21/second at high intensity, and the sync/async switch set in the sync mode. (In this mode, tonepips were gated with constant onset phase and polarity.)

The following peSPL values were measured with dial reading set at 103 dB:

<u>Frequency (Hz)</u>	<u>peSPL</u>
500	133
1000	134
2000	132
4000	134

Therefore, adding 30 dB (± 1 dB) to the dial reading of the CA-1000 at the above frequencies, gives the dBpeSPL value of the tonepip. In the present study, tonepips were presented at a constant dial reading of 55 dBHL corresponding to a constant peSPL value of 85 dB (± 1 dB).

(B) Calibration of Rise/Fall and Plateau Settings

These settings were checked by observation of the waveforms on the oscilloscope. The measured times for rise/fall and plateau were found to agree with the set times to within the accuracy of the measurement (approximately 5%) with two exceptions:

1. At a rise/fall time of 0.5 ms, rise time was approximately 0.4 ms with a marked overshoot on the waveform, while fall time was greater than 1 ms. Due to this anomalous behaviour, a rise/fall time of 1 ms minimum was used.
2. At a plateau time of 0 ms, the waveform appeared to never reach its maximum value, with output level being approximately 9 dB low. Thus, selecting a 0 ms plateau time was not an option.

The use of 2-1-2 cycle stimuli in the present study was therefore subject to the above equipment limitations. In view of this, the rise/fall and plateau times of the tonepip stimuli used were as follows:

<u>Frequency</u>	Rise/Fall (ms)	Plateau (ms)
500Hz	4	2
1000Hz	2	1
2000Hz	1	1
4000Hz	1	1

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