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PERCEPTUAL AND ELECTROPHYSIOLOGICAL  
MASKING OF THE AUDITORY BRAINSTEM RESPONSE

A thesis presented in partial  
fulfilment of the requirements  
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in Psychology at Massey University

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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

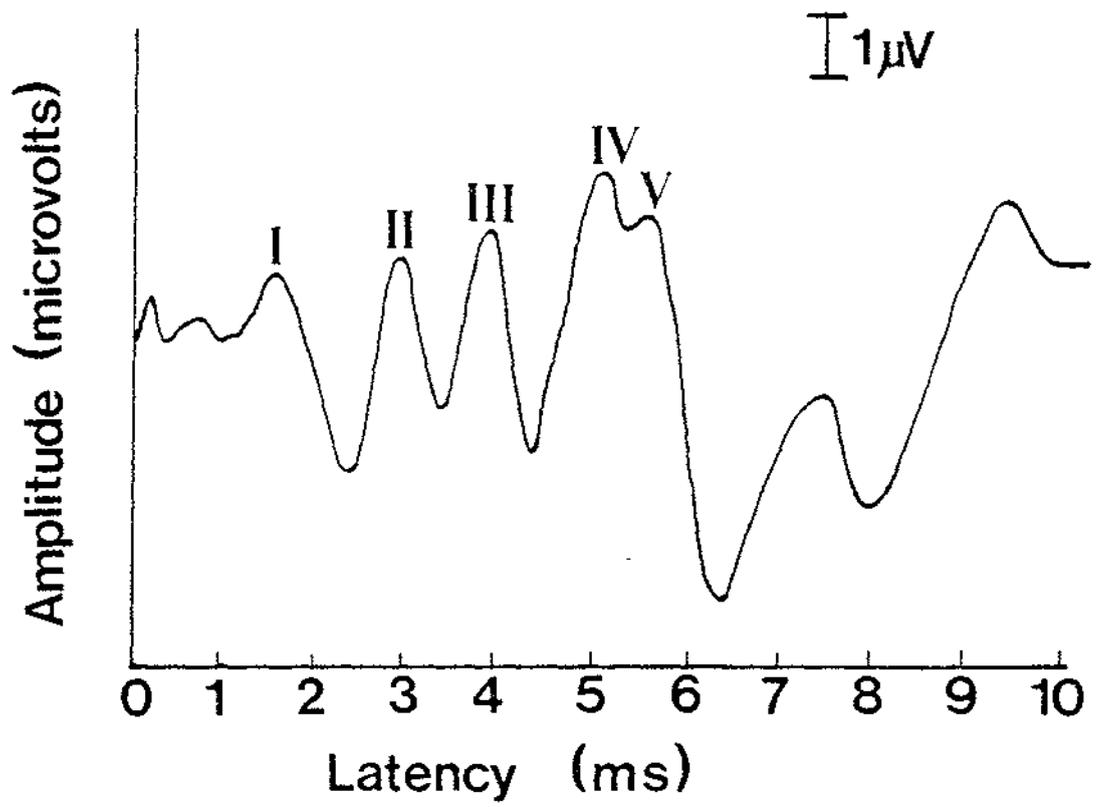


Figure 1. Example of a normal click ABR for an adult male. (from Schwartz and Berry, 1985, p.66).

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

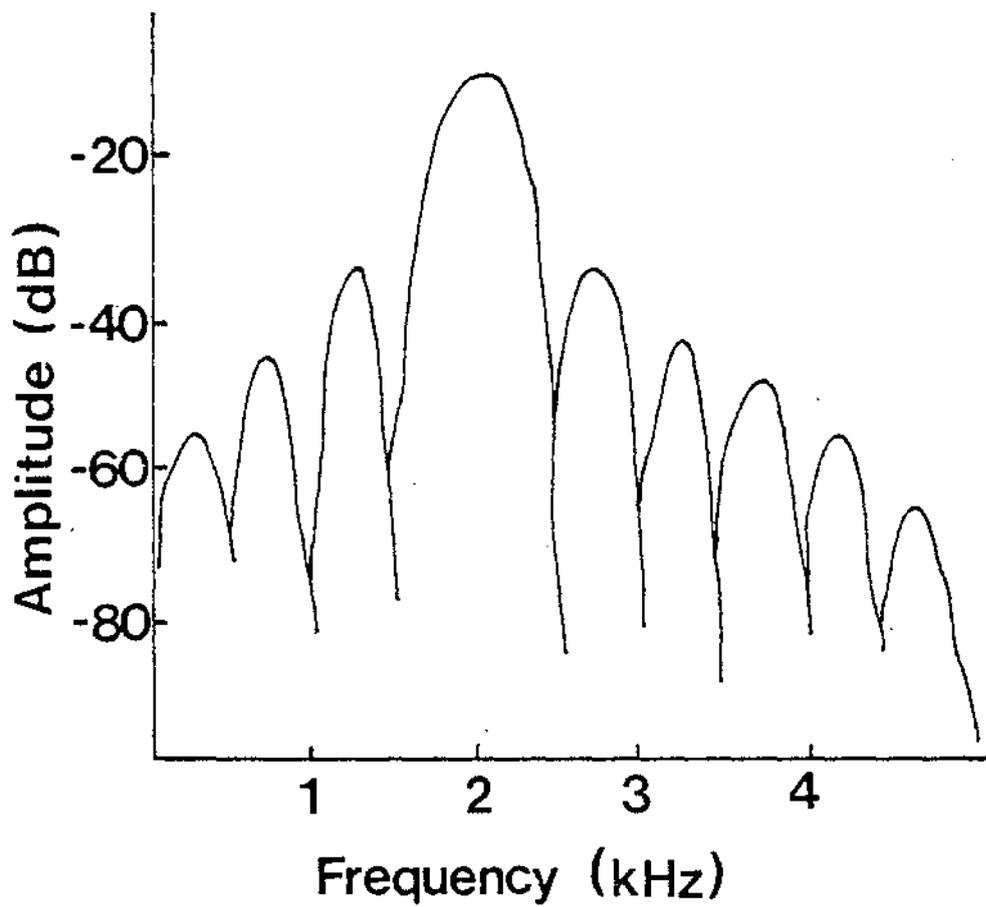


Figure 2. Electrical amplitude spectrum for a 2000 Hz tonepip using a 2 ms linear gating function. (from Gorga, Abbas and Worthington 1985, p. 59).

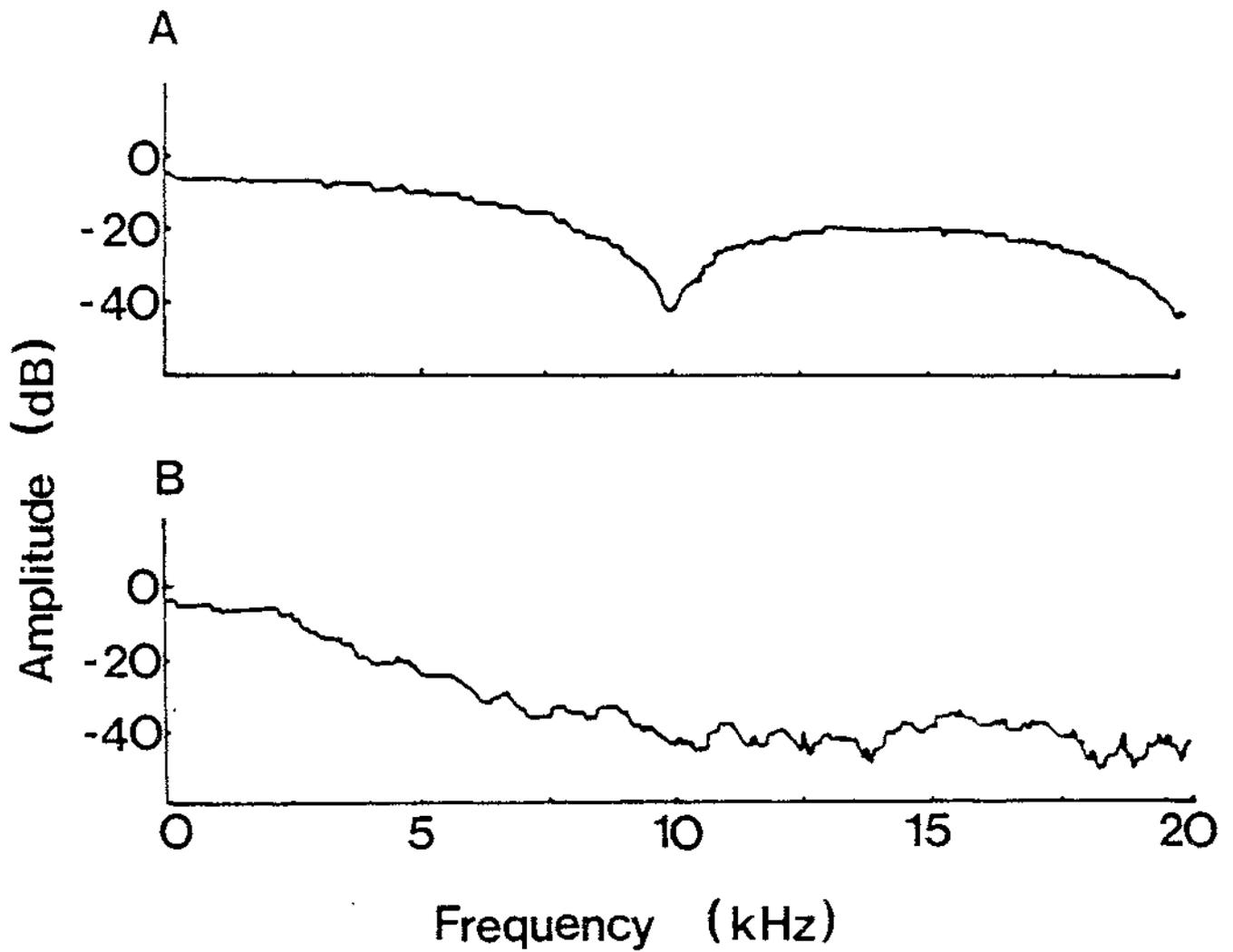


Figure 3. Typical amplitude spectrum for a 100 microsecond click measured (A) electrically and (B) acoustically. (From Gorga, Abbas and Worthington, 1985, p.56).

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, Sohmer 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.