BEHAVIOURAL AND ELECTROPHYSIOLOGICAL
BINAURAL MASKING LEVEL DIFFERENCE

by.

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to the required standard.

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Vancouver, Canada

Date April 25, 2001
ABSTRACT

The binaural masking level difference (BMLD) is a psychoacoustic phenomenon that demonstrates how we benefit from using both ears when detecting signals in noise, especially when they are presented with an interaural phase difference. The behavioural BMLD is believed to reflect brainstem processing. However, this conflicts with results from past research of transient auditory evoked potentials, which suggest that the BMLD is generated at the cortical level and not at the brainstem or thalamus level. The objective of the present study is to investigate the brainstem and cortical mechanisms underlying the BMLD in humans using the auditory steady-state response (ASSR).

A 500-Hz pure-tone, amplitude-modulated (AM) at 80 Hz and 7(or13)-Hz, was used to elicit brainstem and cortical ASSRs, respectively. The masker was a 200-Hz-wide noise centred on 500 Hz. Eleven adult subjects with normal hearing were tested. Both ASSR (brainstem and cortical) and behavioural thresholds for diotic AM stimuli (when the signal and noise are in phase binaurally: S_oN_o) and dichotic AM stimuli (when either the signal or noise is 180° out-of-phase between the two ears: S_oN_o, S_oN_o) were investigated. ASSR and behavioural BMLDs were obtained by subtracting the threshold for the dichotic stimuli from that for the diotic stimuli, respectively. Effects for modulation rate, signal vs noise phase changes, and behavioural vs ASSR measure on the BMLD were investigated.

Behavioural BMLDs (means = 8.5-10.5 dB) obtained are consistent with results from past research. The ASSR results are similar to the pattern of results previously found for the transient auditory brainstem responses and the N1-P2 cortical auditory evoked potentials, such that only the cortical ASSRs (7 or 13 Hz) demonstrate BMLDs (mean = 5.8 dB) but the brainstem ASSRs (80 Hz) (mean = 1.5 dB) do not. This suggests that brain processes underlying the BMLD occur
either in a different pathway or beyond the brainstem auditory processing, and are at or before the
auditory cortical processing. The ASSR results differ from the previous transient N1-P2 studies,
however, in that the cortical ASSRs show a BMLD only when there is a change in the signal
interaural phase, but not for changes of noise interaural phase. This suggests that the cortical
ASSRs are not directly related to the transient N1-P2 responses, and that they may reflect the
output of neural populations which previous research has shown to be insensitive to binaural
differences in noise.
TABLE OF CONTENTS

ABSTRACT .................................................................................................................. ii

TABLE OF CONTENTS ............................................................................................. iv

LIST OF TABLES ........................................................................................................ vii

LIST OF FIGURES ..................................................................................................... viii

NOMENCLATURE ......................................................................................................... ix

PREFACE ..................................................................................................................... x

ACKNOWLEDGEMENTS ............................................................................................ xi

DEDICATION ............................................................................................................... xii

CHAPTER 1: BINAURAL MASKING LEVEL DIFFERENCE .............................................. 1

BEHAVIOURAL STUDIES OF THE
BINAURAL MASKING LEVEL DIFFERENCE ................................................................. 2
  The Phenomenon of the BMLD .................................................................................. 2
  Stimulus Effects on the BMLD .................................................................................... 3
    Presence and Absence of Signal/Masker ................................................................. 3
    Signal Frequency ...................................................................................................... 4
    Interaural Phase and Time Differences of Signal and Masker ......................... 5
    Interaural Level Difference of Signal and Masker .............................................. 6
    Masker Intensity Level ........................................................................................... 6
    Masker Bandwidth .................................................................................................. 6
    Duration of Signal and Masker ............................................................................... 7
    Modulation .............................................................................................................. 8

SITE OF GENERATION OF THE BMLD ................................................................. 9
  Studies of Single Cells ............................................................................................ 9
  Studies of Disorders and Lesions in the Human Central Auditory System ........ 12

MECHANISMS UNDERLYING THE BMLD ............................................................ 14
  Jeffress’s Model ..................................................................................................... 15
  Cross-correlation Model ......................................................................................... 17

CLINICAL IMPLICATIONS OF THE BMLD ......................................................... 19

SUMMARY OF GENERAL FINDINGS OF THE BEHAVIOURAL BMLD .............. 22
CHAPTER 2: AUDITORY STEADY-STATE RESPONSE ........................................... 25

DEFINITION OF THE AUDITORY STEADY-STATE RESPONSE .......... 26
GENERATORS OF THE ASSR ................................................................. 27
  Amplitude Modulation Sensitivity within the Auditory pathway .... 27
  Apparent Latencies of the ASSRs .................................................... 28
  ASSR Studies in Animals ............................................................... 31
  Lesion Studies ............................................................................... 32
  Magnetic and Electrical Source Analysis Studies ....................... 32
RECORDING AND ANALYSIS OF THE ASSR ....................................... 33
  Stimulus ....................................................................................... 33
  Electroencephalogram (EEG) Recording ........................................ 33
  ASSR Analysis ............................................................................. 34
STIMULUS EFFECTS ON THE ASSR .................................................... 36
  Types of Stimulus ........................................................................ 36
  Stimulus Rate and Modulation Rate of Stimulus ....................... 36
  Modulation Depth of AM and FM tones ...................................... 37
  Signal Frequency .......................................................................... 37
  Stimulus Intensity ....................................................................... 38
  Subject Factors .......................................................................... 38
    Arousal State ............................................................................ 38
    Maturation Effect ...................................................................... 39
SUMMARY OF GENERAL FINDINGS OF THE ASSR ......................... 40
PRACTICAL APPLICATIONS AND ADVANTAGES OF THE ASSR .... 41

CHAPTER 3: ELECTROPHYSIOLOGICAL BMLD ......................................... 44

STUDIES ON THE BMLD WITH AUDITORY EVOKED POTENTIALS .... 45
STUDY OF THE BMLD WITH THE ASSR: THE THESIS STUDY .......... 47

CHAPTER 4: BRAINSTEM AND CORTICAL MECHANISMS UNDERLYING
THE BMLD IN HUMANS: AN ASSR STUDY ........................................... 50

INTRODUCTION .................................................................................. 51
METHOD ............................................................................................. 55
  Subjects ....................................................................................... 55
  Stimuli, Maskers, and Conditions ............................................... 56
    Stimuli .................................................................................... 56
    Masker ................................................................................... 56
    Conditions ............................................................................... 56
  Electroencephalogram (EEG) Recording ...................................... 57
  ASSR Analysis ............................................................................ 58
LIST OF TABLES

Table 1: Behavioural Thresholds and BMLDs ......................................................... 62
Table 2: ASSR Thresholds and BMLDs ................................................................. 66
Table 3: Comparison of Behavioural and ASSR BMLDs ....................................... 67
Table 4: Results of the 3-Way Analysis of Variance for the Effects of AM Rate, Behavioural vs ASSR Mode, and Signal vs Noise Polarity Inversion ........... 67
Table 5: Correlation Coefficients between Behavioural and ASSR BMLDs for the 7(or13)-Hz AM Tone and the 80-Hz AM Tone ........................................ 69
LIST OF FIGURES

Figure 1a. FFTs of ASSRs to 500-Hz sinusoid, amplitude modulated at 12.695 Hz for one subject ...................... 64

Figure 1b. FFTs of ASSRs to 500-Hz sinusoid, amplitude modulated at 80.078 Hz for one subject ...................... 65
## NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ABR</td>
<td>auditory brainstem response</td>
</tr>
<tr>
<td>AD</td>
<td>analog-to-digital</td>
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<tr>
<td>ASSR</td>
<td>auditory steady-state response</td>
</tr>
<tr>
<td>APD</td>
<td>auditory processing disorder</td>
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<tr>
<td>AM</td>
<td>amplitude modulated</td>
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<tr>
<td>BMLD</td>
<td>binaural masking level difference</td>
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<tr>
<td>CAEP</td>
<td>cortical auditory evoked potential</td>
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<tr>
<td>CD</td>
<td>characteristic delay</td>
</tr>
<tr>
<td>CF</td>
<td>characteristic frequency</td>
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<tr>
<td>DA</td>
<td>digital-to-analog</td>
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<tr>
<td>dB</td>
<td>decibel</td>
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<tr>
<td>EEG</td>
<td>electroencephalogram</td>
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<tr>
<td>EP</td>
<td>evoked potential</td>
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<tr>
<td>FFT</td>
<td>fast Fourier transform</td>
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<tr>
<td>ILD</td>
<td>interaural intensity difference</td>
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<tr>
<td>IPD</td>
<td>interaural phase difference</td>
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<tr>
<td>ITD</td>
<td>interaural time difference</td>
</tr>
<tr>
<td>MEG</td>
<td>magnetoencephalography</td>
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<tr>
<td>MF</td>
<td>modulation frequency</td>
</tr>
<tr>
<td>MLR</td>
<td>middle latency response</td>
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<tr>
<td>MSO</td>
<td>medial superior olive</td>
</tr>
<tr>
<td>MTF</td>
<td>modulation transfer function</td>
</tr>
<tr>
<td>N</td>
<td>noise</td>
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<tr>
<td>N&lt;sub&gt;m&lt;/sub&gt;</td>
<td>monaural noise (monotic noise)</td>
</tr>
<tr>
<td>N&lt;sub&gt;o&lt;/sub&gt;</td>
<td>noise in-phase binaurally (diotic noise)</td>
</tr>
<tr>
<td>N&lt;sub&gt;x&lt;/sub&gt;</td>
<td>noise 180° out-of-phase between the two ears (dichotic noise)</td>
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<tr>
<td>S</td>
<td>signal</td>
</tr>
<tr>
<td>S&lt;sub&gt;m&lt;/sub&gt;</td>
<td>monaural signal (monotic signal)</td>
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<td>signal 180° out-of-phase between the two ears (dichotic signal)</td>
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<td>diotic signal and dichotic noise</td>
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<tr>
<td>SPL</td>
<td>sound pressure level</td>
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<td>(\tau)</td>
<td>interaural time delay</td>
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PREFACE

This thesis consists of four chapters: (1) a review of the literature on the binaural masking level difference, (2) a review of the literature on the auditory steady-state response, (3) a review of the literature on the electrophysiological binaural masking level difference, and (4) a research paper in which auditory steady-state response was used to study the brainstem and cortical mechanisms underlying the binaural masking level difference. Readers will find certain information overlapped between the research paper in Chapter 4 and the literature reviews in the first three chapters.
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I would like to express my special thanks to Dr. David Stapells for his continuous guidance, support, and commitment to my thesis study. I feel privileged to be your student and to work with you in the research. Your sharp eyes and warm heart have inspired me to greater efforts.

I am grateful to Anna Van Maanen for extending herself all the way to help me accomplish this dissertation. Thank you very much for your kindness and understanding.

I also thank the participants and colleagues of the UBC Human Auditory Physiology Laboratory for enduring the long hours of electroencephalogram recording. Your contribution and support are much appreciated.

Grateful acknowledgement is extended to the Natural Sciences and Engineering Research Council of Canada and the Canadian Institutes of Health Research for their generous support of this study.

Most importantly, I thank my heavenly Father, who answers me even before I ask.
To my Lord and my family,
who both love me unconditionally
CHAPTER 1:

BINAURAL MASKING LEVEL DIFFERENCE
The Phenomenon of the BMLD

The binaural masking level difference (BMLD) is a psychoacoustic phenomenon that demonstrates how we benefit from using both ears instead of one when detecting signals in noise, especially when they are presented with an interaural phase or level difference. In the classical BMLD experiment, the threshold of a signal in noise is determined by presenting the signal (S) and noise (N) to one ear, i.e., monaurally, which serves as the reference condition (S_mN_m) (Hirsh, 1948; Jeffress, Blodgett, & Deatherage, 1952). The configurations of the signal and/or noise are then manipulated at the two ears in various conditions and the masked threshold (in dB) of the signal determined in each condition. The reduction in the masked signal threshold in various manipulated interaural conditions compared to that in the reference monaural case is referred to as the BMLD. Such improvement in signal threshold may also be described as a binaural release from masking (Moore 1997, p. 238). The variables to be manipulated interaurally may include the absence/presence of the signal and masker, the type of the signal and masker, the frequency of the signal and the frequency content and bandwidth of the masker, the phase configuration of the signal and masker, the level of the masker, the duration and relative temporal positions of the signal and masker, and modulation of the signal and masker (Grantham, 1995).

An illustration of the BMLD contributed by the interaural phase difference is described below. Past research has shown that the masked threshold of a signal is the same when the signal (S) and noise (N) are presented to only one ear (S_mN_m, monotonic condition) or when the signal and noise are presented in phase binaurally (S_oN_o, diotic condition) (Sever & Small, 1979). Therefore, either the monotonic or the diotic condition may be used as the reference condition to calculate the BMLD. On the other hand, the masked threshold of the signal in the monotonic or diotic reference
condition is higher than that for dichotic conditions in which either the signal or the noise is 180° out-of-phase between the two ears (S_N_o, S_o_N_o) (Hirsh, 1948; Jeffress, Blodgett, & Deatherage, 1952). That is, an increase in detectability of the signal in noise is achieved when either the signal or the noise is 180° out-of-phase between the two ears.

According to Hirsh (1948), the signal threshold is highest for the S_N_m (dichotic signal and dichotic noise) and S_o_N_o (diotic signal and diotic noise) conditions, followed by the S_m_N_m (monotic signal and dichotic noise) and S_N_m conditions (dichotic signal and monotic noise), then by the S_o_N_m (diotic signal and dichotic noise) and S_N_o (dichotic signal and diotic noise) conditions. Subtracting the threshold (in dB) for the dichotic stimuli from that for the diotic or monotic stimuli (S_o_N_o, S_m_N_m) gives a difference threshold, representing the BMLD. Thus, the largest BMLD value is obtained when the polarity of either the signal or the noise is inverted in one ear relative to the other. A maximum behavioural BMLD of 12-15 dB was found for the condition S_N_o with signal frequencies of 200 Hz and 500 Hz (Hirsh, 1948).

The BMLD may also be observed for stimuli other than pure-tones, e.g. complex tones, clicks, and speech sounds (Moore, 1997, p. 237).

Stimulus Effects on the BMLD

Presence and Absence of Signal/Masker. In the absence of any interaural differences in a broadband noise presented to both ears, the presence of a 500-Hz signal in one ear but not the other will enhance its detection (Durlach & Colburn, 1978; McFadden, 1968). That is, when compared with the monaural condition S_m_N_m, a BMLD is observed when an identical masker is added to the non-signal ear, resulting in the S_m_N_o condition. If an identical signal is then added to
the originally non-signal ear, no BMLD is observed (Durlach & Colburn, 1978; Sever & Small, 1979). That is, the masked threshold is the same for the $S_m N_m$ and $S_o N_o$ conditions.

**Signal Frequency.** The BMLD obtained between the $S_o N_o$ and $S^N_o$ conditions may be expressed as a function of the frequency of the masked signal. As the signal frequency increases, the BMLD decreases, but it never goes to zero (Hirsh, 1948; Yost, 1994, p. 180). That is, such binaural advantage always exists and it is always easier to detect a signal in the dichotic conditions than in the diotic or monotic conditions. The BMLD would be expected to be larger for lower signal frequencies, because low frequencies may be coded by a phase locking mechanism in the peripheral auditory system, whereas phase locking is not present for higher frequencies (Moore, 1997, pp. 237-238; Yost, 1997, pp.123-125). Using 50-Hz-wide bands of noise with centre frequencies of 250, 500, 1000, 2000, and 4000 Hz as maskers and signals, McFadden and Pasanen (1974) found that a larger BMLD is obtained for low frequencies than for high frequencies. Moreover, the auditory system appears to be able to process both interaural time and level differences for low-frequency stimuli, whereas for high-frequency stimuli (at 2000 and 4000 Hz), the auditory system is not as able to utilize both binaural cues. It appears to perform better with the interaural level differences than the interaural time differences for high-frequency stimuli (McFadden & Pasanen, 1974).

For broadband noise and low-frequency signals, the BMLD for condition $S_m N_o$ may reach as high a value as 15 dB, whereas the highest value of the BMLD falls to 2-3 dB for signal frequencies above about 1500 Hz (Moore, 1997, p. 237). However, larger BMLDs may also occur for high signal frequencies when the masker is a narrowband noise (McFadden, Jeffress, & Ermey, 1972).
Interaural Phase and Time Differences of Signal and Masker. The largest BMLD value occurs when the polarity of either the signal or the masker is inverted (i.e., 180° out-of-phase) in one ear relative to the other (Hirsh, 1948; Jeffress, Blodgett, & Deatherage, 1952). For low-frequency signals, the value of the BMLD increases as the signal interaural phase difference (IPD) increases from 0° to 180° (Colburn & Durlach, 1965; Hirsh, 1948; Jeffress, Blodgett, & Deatherage, 1952). The effect on the BMLD is similar when the masker IPD is changed, keeping the low-frequency signal IPD in phase between the ears (Jeffress et al., 1952). In general, for low-frequency signals, the BMLD as a function of signal IPD change rises more steeply and attains a higher value than the BMLD as a function of noise IPD (Durlach & Colburn, 1978). That is, a larger BMLD is generally observed when the IPD of the signal increases from 0° to 180°.

Langford and Jeffress (1964) manipulated the noise correlation by introducing a time delay into a 500-Hz noise component channel to one ear, while determining the masked threshold for a 500-Hz signal in the $S_0N_0$ and $S_0N_0$ conditions. Nineteen interaural time differences (ITDs) in the noise, ranging from 0 ms to 9 ms, were studied. The largest BMLD is obtained when the time delay of the noise is such that the signal is inverted at one ear ($S_0$) and the noise is in phase at both ears ($N_0$), followed by that obtained in the condition where the signal is in phase at both ears ($S_0$) but the noise is delayed by 1 ms at one ear, creating the $S_0N_0$ condition. For delays that result in a quadrature phase relationship of the noise between the two ears, the masked thresholds of $S_0$ and $S_0$ are indistinguishable. That is, no obvious BMLD is observed. Langford and Jeffress (1964) concluded that for the antiphasic conditions $S_0N_0$ and $S_0N_0$, reducing the noise correlation between the two ears by adding a time delay in one noise channel would produce a reduction in the BMLD.
**Interaural Level Difference of Signal and Masker.** The BMLD may also be expressed as a function of the interaural level difference (ILD) of the signal (Colburn & Durlach, 1965) and masker (McFadden, 1968). For signals, an interaction of the function with the signal IPD is observed. For a 500-Hz signal, the BMLD increases as the interaural level difference increases (Colburn & Durlach, 1965). For maskers, detectability is best when a signal is presented to only one ear ($S_m$) with the noise presented to both ears having the same intensity level (McFadden, 1968). The signal detectability, and hence the BMLD, decreases as the noise ILD increases.

**Masker Intensity Level.** In normal-hearing listeners, the BMLD increases as a function of the masker intensity level, ranging from 50 to 100 dB SPL (Durrant, Nozza, Hyre, & Sabo, 1984; Hirsh, 1948; McFadden, 1968). The growth of BMLD versus noise intensity function either decreases at high-intensity levels (Durrant, Nozza, Hyre, & Sabo, 1984; Hirsh, 1948) or reaches a plateau at about 40 dB above the noise intensity level at which the BMLD first occurs (McFadden, 1968). For listeners with a hearing loss, similar growth of the BMLD-noise intensity function has been observed, even at high masker intensity levels (Durrant et al., 1984). Yost (1988), however, suggested that the small BMLD observed at low masker levels might be contaminated by the additive internal noise related to using supraaural earphones. Since internal noise is at least partially interaurally uncorrelated, smaller BMLDs might be obtained as a result of decreased correlation of the masker at low levels. Yost thus suggested that the BMLD may depend less on the masker level with insert earphones than with supraaural earphones (Yost, 1988).

**Masker Bandwidth.** For both monaural masking and binaural masking, not all frequency components within a wideband masker are effective in masking a signal (Moore, 1997, pp. 111-118). Although broadband noise can yield large behavioural BMLDs for low-frequency signals,
Moore points out that only those masker frequency components around the signal frequency are
effective in masking the signal, and thus the release from masking seen in BMLD conditions also
depends on such frequency components (Moore, 1997, p. 238). There has been some
disagreement, however, as to whether the monaural critical bandwidth is the same as the binaural
critical bandwidth (Langford and Jeffress, 1964; Moore, 1997, p. 238).

Wightman (1970) investigated the effect of masker bandwidth on the BMLD for low-
frequency signals. He found that, with the polarity of the signal inverted, the BMLD increased
markedly with reduction in masker bandwidth from 200 Hz to 3 Hz. Similar results were also
obtained by Bourbon and Jeffress (1965). This relationship is only achieved, however, when the
off-frequency energy ("splatter"), created by turning the signal on and off, is eliminated by
filtering (Wightman, 1970). The masker-bandwidth effect is also observed for high-frequency
signals (McFadden, Jeffress, & Ermey, 1972). In addition, hearing-impaired listeners show
abnormally small BMLDs in wideband noise (2000-Hz wide) but not in narrowband noise (50-Hz
wide) for a 500-Hz signal (Hall & Harvey, 1985). When the BMLD in children is compared with
that of adults (for a 500-Hz signal), as a function of masker bandwidth, children younger than
about seven years of age demonstrate smaller BMLDs for narrowband (20-Hz wide) noise but not
for wideband (320-Hz wide) noise (Grose, Hall, & Dev, 1997).

Duration of Signal and Masker. In general, for low-frequency signals (200-800 Hz),
reducing the signal duration from around 300 ms to approximately 10 ms results in either a slight
increase of the BMLD value (~1.5-2.5 dB) for the dichotic conditions $S_nN_o$ (Bernstein &
Trahiotis, 1999; Kohlrausch, 1986) and $S_oN_s$ (Kohlrausch, 1986) or no effect on the BMLD
(Zwicker & Zwicker, 1984). In contrast, for high-frequency signals (e.g., 4000 Hz), the same
decrease of signal duration results in a substantial decrease (~4.5 dB) in the BMLD for the $S_nN_o$.
condition. This differential effect of signal duration on the BMLD may suggest different binaural processing mechanisms underlying low- and high-frequency signals (Bernstein & Trahiotis, 1999).

As far as masker duration is concerned, for low-frequency signals (200-800 Hz), a decrease from 500 to 25 ms in masker duration reduces the BMLD value by 7-11 dB for dichotic conditions $S_aN_o$ and $S_oN_o$ (Kohlrausch, 1986). A decrease of about 5-10 dB in the BMLD was also reported as the masker duration decreased from 200 ms to 10 ms for low-frequency signals (Zwicker & Zwicker, 1984). Differences in the detection mechanisms involved in monaural and binaural masking has been hypothesized (Kohlrausch, 1986).

Past research has also shown that a measurable BMLD may occur when the signal and masker are separated by a silent interval of up to 40 ms (Moore, 1997, p. 239), and both forward and backward masking can yield BMLDs (Dolan & Trahiotis, 1972; Small, Boggess, Klich, Kuehn, Thelin, & Wiley, 1972).

**Modulation.** In general, as the depth of noise modulation increases, the behavioural BMLD also increases. Envelop fluctuation of a narrowband masker (Eddins & Barber, 1998) or intensity modulation of a wideband noise (Hall and Fernandes, 1983), which acts as both masker and signal, makes signal detection in the non-inverted $S_oN_o$ condition more difficult, whereas signal detection in the $S_aN_o$ condition is subject dependent. Using a 500-Hz tone as the signal and a 10-Hz wide noise as the masker, Hall, Grose, and Hartmann (1998) demonstrated that signal detection was improved for the $S_oN_o$ condition with decreasing degree of noise fluctuation. That is, as the depth of modulation of the noise increases, the $S_oN_o$ masked threshold also increases. For the $S_aN_o$ condition, however, results tend to be subject dependent. For half of the subjects that Hall et al. studied, the $S_aN_o$ masked threshold was not affected by the depth of noise modulation.
For the others, signal detection was improved with increasing degree of noise modulation, indicating that a high degree of masker fluctuation may sometimes facilitate S\textsubscript{4}N\textsubscript{0} detection (Hall et al., 1998). To date, it does not appear that the effect of amplitude modulation of the signal on the behavioural BMLD has been studied.

**SITE OF GENERATION OF THE BMLD**

After leaving the cochlea, auditory information is transmitted by the auditory nerve to the ipsilateral cochlear nucleus. The afferent fibres then travel from the ipsilateral cochlear nucleus to the ipsilateral and contralateral superior olivary complexes in the pons of the brainstem, at and above which bilateral representation occurs. There is also a pathway from the ipsilateral cochlear nucleus to the contralateral inferior colliculus, ascending along the lateral lemniscus and bypassing the superior olivary complexes. From the superior olivary complexes, bilateral information is transmitted along the lateral lemniscus to the inferior colliculus, then to the medial geniculate body, and finally to the auditory cortex. Since auditory input information from both ears reaches the superior olivary complexes both ipsilaterally and contralaterally, it is reasonable to believe that the BMLD is generated at and/or above this brainstem level.

**Studies of Single Cells**

Studies of single cells (or groups of cells) along the auditory pathway have shed light on the site of generation of the BMLD. Past experiments on anaesthetized cats reveal that about two-thirds of the medial superior olivary neurons are sensitive to ITD whereas the majority of the lateral superior olivary neurons are sensitive to ILD (For review, see: Brugge, 1992). Low-frequency signals are transmitted with high fidelity from the cochlea nucleus to the ipsilateral and
contralateral medial superior olivary neurons by means of phase locking. The bilateral phase-locking information, which underlies the sensitivity to IPD, is then processed by the inferior colliculus (Brugge, 1992). Yin and Chan (1988) found that the ITD sensitivity exhibited by the inferior colliculus closely reflected the binaural mechanisms in the superior olivary complex. Research on single cells in the inferior colliculus in cats (Yin & Kuwada, 1984) and in rabbits (Kuwada, Stanford, & Batra, 1987) reveals that when low-frequency tones are delivered to the two ears, IPD (and hence ITD) sensitivity is exhibited by neurons along the pathway of the lateral lemniscus (Brugge, 1992). Cells sensitive to the IPD are also found at levels above the inferior colliculus in the auditory system, namely the medial geniculate body (Aitkin & Webster, 1972) of cats and the auditory cortex (Brugge & Merzenich, 1973) of monkeys.

Caird, Pillmann, and Klinke (1989) reported that the majority of neurons in the cat inferior colliculus responded better to stimuli presented in-phase between the two ears (in-phase stimuli), whereas a minority of cells responded better to stimuli presented out-of-phase between the two ears (out-of-phase stimuli). However, Caird et al. (1989) did not find any cells that specifically coded the BMLD. That is, cells that respond best either to the out-of-phase signal in the in-phase noise condition (i.e., $S_xN_o$) or to the in-phase signal in the out-of-phase noise condition (i.e., $S_oN_x$) are not found. Interestingly, the synchronized spike rates of some neurons that fire in response to in-phase stimuli are strongly suppressed by out-of-phase noise, but the synchronized spike rates of others are strongly suppressed by in-phase noise. Thus, the same type of neurons may show a low or high threshold to a signal in noise, depending on the type of noise by which the neurons are strongly suppressed. Over the whole population of cells studied by Caird and colleagues, suppression of the synchronized neuronal spike rates by noise cancels out
and the neuronal threshold does not appear to be significantly affected by the BMLD configuration (Caird et al., 1989).

Studies with chinchillas and guinea pigs reveal different results. Mandava, Rupert and Moushegian (1996) discovered that among the 71 chinchilla inferior colliculus neurons they studied, the number of neurons driven by an in-phase low-frequency signal \( S_0 \) is approximately equal to the number of neurons driven by an out-of-phase signal of the same frequency \( S_K \). However, when an in-phase masker is added to the signal, some neurons respond better to dichotic \( S_xN_o \) sounds than to diotic \( S_oN_o \) sounds. A differential response of the neurons to the dichotic and diotic conditions is noted for signal-to-noise ratios from -25 dB to 0 dB (Mandava et al., 1996).

In contrast, research with guinea pigs has shown that the discharge rate of inferior colliculus neurons to low-frequency tones in noise is generally consistent with the human behavioural BMLDs (Caird, Palmer, & Rees, 1991; Jiang, McAlpine, & Palmer, 1997a, b; Palmer, Jiang, & McAlpine, 1999, 2000). Caird et al. (1991) demonstrated that the effects of masking for low-frequency cells in the inferior colliculus of guinea pigs are similar to the human BMLD. Caird et al. (1991) recorded the spike rates of the inferior colliculus neurons to a 50-ms signal (a low-frequency tone burst or a synthetic vowel segment) in noise at the best interaural delay of the unit. They found that the mean difference between the maximum masked thresholds across the cell population resembled the human BMLD under the same signal and masker conditions, suggesting that the behavioural BMLD is the result of auditory processing at levels up to and including the inferior colliculus (Caird et al., 1991).

Jiang et al. (1997a) and Palmer et al. (1999, 2000) also found that the responses of inferior colliculus neurons in guinea pigs are comparable to human psychophysical BMLDs when either
the signal or the noise is inverted at one ear. Detection of a 500-Hz signal in both $S_0N_0$ and $S_\pi N_0$ conditions is attributable to the same population of neurons with their best frequency near 500 Hz (Jiang et al., 1991a, b). Among this population of neurons, however, the presence of the inverted tone ($S_\pi$) at one ear is indicated by an increased discharge rate in some neurons but a decreased discharge rate in others (Jiang et al., 1991b). Similarly, Palmer et al. (1999) reported that, in the presence of a fully correlated wideband noise, an inverted 500-Hz tone ($S_\pi$) at one ear was more detectable in individual neurons at a lower level than the non-inverted tone ($S_0$), although the $S_\pi$ tone caused a reduction in the discharge rate of some units but an increase in discharge rate of others. Interestingly, when the polarity of the noise is inverted in the presence of a fully correlated signal, the diotic signal ($S_0$) is detectable at a lower level in $N_\pi$ noise than in $N_0$ noise in only 33 out of 62 neurons (Palmer et al., 1999). In a more recent study, Palmer et al. (2000) reported that the majority of guinea pig inferior colliculus neurons demonstrate that the direction of discharge rate change is consistent with psychophysical observations. A smaller BMLD value around the 500-Hz best frequency is recorded for the $S_0N_0$ versus $S_0N_\pi$ condition than the $S_0N_0$ versus $S_\pi N_0$ condition.

**Studies of Disorders and Lesions in the Human Central Auditory System**

Listeners with disorders or lesions in the auditory system have been found to demonstrate pathological behavioural BMLDs. Past research has suggested that pathological behavioural BMLD is correlated with an abnormal ABR (see below) (Ferguson, Cook, Hall, Grose, & Pillsbury, 1998; Gravel, Wallace, Ruben, 1996; Hannley, Jerger, Rivera, 1983; Noffsinger, Martinez, & Schaefer, 1982), further suggesting that the BMLD reflects brainstem processing. Gravel et al. (1996) investigated seven children who had experienced repeated episodes of otitis
media and mild conductive hearing loss during their first year of age, and compared them with 10 children who were otitis media free over the same age range. The investigators further studied these children's auditory brainstem response (ABR) threshold at one year of age and compared it with their behavioural BMLD at nine years of age. Gravel et al. (1996) found that the behavioural BMLD at age nine was correlated with the children's first-year click-ABR thresholds that fell in the range of the mild hearing loss. Children with otitis media in their early life demonstrate smaller behavioural BMLD values at the age of nine. Gravel et al. (1996) hypothesized that higher-order binaural processing such as reflected by the BMLD may be influenced by hearing loss experienced by some children in their early life. When adult listeners with chronic mild-to-moderate unilateral conductive loss are compared with normal-hearing listeners, a smaller BMLD observed in the former group is related to their pathological ABR, independent of the hearing threshold (Ferguson et al., 1998). The behavioural BMLD is significantly and positively correlated with the I-V and I-III interwave latencies, but not with the absolute ABR wave latencies nor the III-V interwave latency (Ferguson et al., 1998). The correlation found by Ferguson et al. (1998) suggests that the behavioural BMLD is generated in the lower brainstem, because the main generators of wave III are at or above the pontine tegmentum and/or in the superior olivary complexes (For review, see: Legatt, Arezzo, & Vaughan, 1988).

Listeners with retrocochlear disorder also show abnormally small behavioural BMLDs. Noffsinger et al. (1982) studied 20 patients with either brainstem or VIIIth nerve lesions and compared their behavioural BMLD with their ABR results. Patients with abnormal ABR waves I, II, or III demonstrate small or no behavioural BMLD, whereas patients with abnormal brainstem potentials IV or V and normal I-III interpeak latencies have normal behavioural BMLD (Noffsinger et al., 1982). Noffsinger and colleagues thus suggest that the size of the behavioural
BMLD is related to the generation of the early auditory brainstem potentials. Similarly, patients with multiple sclerosis who lack wave III of the ABR have also demonstrated no release from masking: that is, no BMLD was obtained. Thus, when asked to detect a 500-Hz tone in broadband noise in the conditions S\textsubscript{0}N\textsubscript{0} and S\textsubscript{rt}N\textsubscript{0}, listeners with multiple sclerosis who show abnormal ABR wave III demonstrate an abnormal reduction in their behavioural BMLD. Hannley and colleagues conclude that the size of the behavioural BMLD varies with the integrity of wave III of the ABR, and that the sensitivity of the behavioural BMLD to retrocochlear disorder is comparable to that of the ABR (Hannley et al., 1983).

Thus, studies of the relationship between the site of lesions and disorders along the auditory pathways and the pathological behavioural BMLDs point to the direction that the brainstem, most probably at the level of the pons, may be one of the generation sites of the BMLD.

**MECHANISMS UNDERLYING THE BMLD**

Over the past few decades, several models have been developed to account for the binaural interaction of auditory input to the central auditory system. The physical basis of the benefits of hearing with two ears instead of one, in the horizontal plane, lies in the differences in intensity and/or time of arrival of a sound at the two ears (Brugge, 1992; Yin & Kuwada, 1984; Yin & Chan, 1988). The differences of detectability of various BMLD conditions are believed to be related to the fact that our auditory system is capable of making use of binaural cues to detect signals in noise, especially the interaural temporal difference cues for low-frequency signals (Moore, 1997, pp. 235-230; Yost, 1994, pp. 170-181). High precision in neural synchrony is believed to be involved in the detection of the interspike time that gives information on the low-
frequency signals in noise, especially in dichotic conditions (Yin & Kuwada, 1984; Yin & Chan, 1988). Because larger values of the BMLD are observed for lower signal frequencies, it is likely that the BMLD depends to some extent on the transmission of the temporal information of the signal to some higher neural centres that integrate such information from the two ears (Moore, 1997, p. 238). Two models, Jeffress’s model and the cross-correlation model, based on the sensitivity of the auditory system to the IPD and ITD will be described below. Jeffress’s model accounts for the binaural interaction of stimuli, which was subsequently extended to become the cross-correlation model to account for the mechanism of the BMLD.

**Jeffress’s Model**

The binaural model to account for our ability to localize low-frequency sounds by using interaural time differences was originally proposed by Jeffress (1948). In Jeffress’s model, there are a network of neurons at the level of the midbrain that fire only when the inputs from the two ears reach the same neuron at the same time. These neurons are known as “coincidence detectors”. A specific coincidence neuron will respond highest to inputs with a specific interaural time delay (“characteristic delay”). For example, for a coincidence neuron that fires maximally to a delayed input of 50 µs from the left ear compared to the right ear, the inputs from the two ears will coincide at the coincidence neuron if the sound arrives at the left ear 50 µs earlier at the left ear than at the right ear. Thus, sounds arriving at the two ears at different time intervals will evoke the strongest response in a specific coincidence detector. Since a characteristic delay may correspond to a certain azimuth, the entire range of azimuths may be covered by delays that range from 0 to 650 µs (90° azimuth corresponds to 650 µs) in humans (Møller, 2000, p. 247).
Building on Jeffress's model, Webster (1952) proposed that the change in interaural time delay caused by a change in the configuration of the signal at one ear would contribute to easier detection of the signal in broadband noise. Assuming that the total stimulus to each ear was filtered in the auditory system by a narrow critical band centred at the characteristic frequency of the signal, Webster (1952) postulated that the neuronal output would give information on the presence of the target signal.

Studies of single cells have supported Jeffress's model and the existence of coincidence detectors. Animal data reveals that a topographic organization of neuronal sensitivity to ITD exists in the medial superior olive (MSO). Neurons located rostrally in the MSO respond maximally at zero ITD, whereas neurons located more caudally in the MSO respond maximally at progressively larger ITDs. Within this ITD topography, iso-ITD contours can be traced from the ventral to dorsal of the MSO. Each iso-ITD contour represents a specific ITD that produces the maximum neuronal discharge (Irvine, 1992). The afferent fibres to the MSO are so arranged that the ipsilateral path length to a certain neuron that is sensitive to a specific ITD is longer than the contralateral path length to the same neuron. Thus, the phase-locking information from both ears reach the same coincidence detecting neuron simultaneously due to the difference in conduction time for the ipsilateral and contralateral input (Carr and Konishi, 1990).

The majority of neurons in the MSO with characteristic frequencies less than 1 kHz are sensitive to the ITD and IPD (Brugge, 1992). When the MSO receives inputs directly from the ipsilateral and contralateral anteroventral cochlear nuclei, the shorter path length of the low-frequency fibres and the tight synapse between the MSO neurons and anteroventral cochlear nucleus neurons enables secure and accurate matching of the temporal patterns of the waveforms
from the two ears. High-frequency fibres, on the other hand, travel a longer path length into the brainstem before they bifurcate (Irvine, 1992).

Interaural phase-sensitive units were also found in the inferior colliculus of cats (Yin & Kuwada, 1984) and unanesthetized rabbit (Kuwada et al., 1987). Peak neuronal discharge was recorded in binaural cells at which excitatory inputs from each ear converged simultaneously. Although the majority of inferior colliculus units showed interaural phase sensitivity to frequencies below 1500 Hz, some were found to be sensitive to frequencies as high as 2150 Hz (Kuwada et al., 1987).

Cross-correlation Model

Jeffress’s model has been extended to account for the phenomenon of the BMLD by means of a cross-correlation model that incorporates the neuronal response pattern of the auditory system. For instance, Colburn (1973, 1977) and Stern and Trahiotis (1995) have presented a cross-correlation model in which a correlation between the two signals arriving at the two ears at a specific interaural time delay is established by the network of neurons as a function of the interaural time delay (τ) and characteristic frequency (CF). The internal pattern of the output of a specific coincidence neuron is represented by such a correlation. Colburn (1973, 1977) proposes that a “binaural displayer” is situated along the path of the auditory system, which acts as a decision maker. An estimate of the cross-correlation of the two waveforms arriving at the two ears is derived from the instantaneous interaural time delay, the amplitude of the instantaneous rate of monaural fibres, and the CF of the fibres. The phase-locked information from the two ears are thus transformed into such a cross-correlation function. The binaural displayer then makes a
judgement about the binaural input signal on the pattern of the neuronal response activity (Colburn & Durlach, 1978).

Stern and Trahiotis (1995) propose that when the binaural signals are identical and in phase, a highest value of cross-correlation of the two signals is demonstrated by neurons with characteristic delay (CD) at $\tau = 0$ and CF equals to the signal frequency. For a broadband noise arriving in phase at the two ears, the highest value of cross-correlation of the binaural noise is demonstrated by neurons with CD at $\tau = 0$ and CFs over a broad range of frequencies. When two identical signals are temporally shifted at a specific time delay ($\tau = 0$), the highest value of cross-correlation of the binaural signals are demonstrated by neurons with a specific CD and CF equals to the signal frequency.

Stern and Trahiotis (1995) illustrate the cross-correlation mechanism by means of computational analysis using a 500-Hz tone signal and a broadband masking noise presented in the $S_0N_0$ and $S_\pi N_0$ conditions. At a signal-to-noise ratio (SNR) of -20 dB, the addition of an in-phase signal ($S_0$) to the in-phase noise ($N_0$) has no effect on the cross-correlation between the two signals and maskers at the two ears, since the internal delay is unchanged. The signal is not detected because the response pattern of the binaural system is not affected in terms of cross-correlation. However, when an out-of-phase signal ($S_\pi$) is added to the in-phase noise ($N_0$) at the same SNR, the masker components are cancelled near the signal CF, i.e., around 500 Hz. The change in the pattern of output by the neural responses of the binaural system enables easy detection of the out-of-phase signal, and hence the BMLD.

Palmer and colleagues (1999) support the cross-correlation model by demonstrating that the addition of an out-of-phase 500-Hz signal to a fully correlated noise has a similar effect on the discharge rate of the guinea pig inferior colliculus neurons as when the binaural noise is
decorrelated. This desynchronizing effect of the noise components on the coincidence detector is consistent with the cross-correlation model. In both cases, the detectability of the out-of-phase signal is improved.

Although Jeffress’s model and the cross-correlation model are satisfactory in explaining most of the BMLD conditions, they fail to predict interaural level difference (ILD) results. Moreover, the models described so far do not account for the fact that the BMLD increases with the masker level, as revealed by the behavioural data. Also, the mechanism and effect of the internal noise in the auditory system is not satisfactorily addressed. Finally, the detection of high-frequency signals in a masker demands a more-appropriate model other than the ones described above. It has been suggested that neurons may phase-lock to the modulating envelope of the stimulus from either ear (Yin & Kuwada, 1984), or the ILD of high-frequency signals is utilized for their detection in noise, or some other methods of processing are involved (Hirsh, 1948; Colburn & Durlach, 1978).

CLINICAL IMPLICATIONS OF THE BMLD

Zurek proposes a quantitative model to predict the binaural advantages and directional effects in speech intelligibility in normal-hearing listeners. He suggests that speech detectability may be reflected by the BMLD, which in turn increases with speech intelligibility. Normal-hearing listeners may thus perceive speech in a more-clear, louder, and less-contaminated manner in the presence of background noise and/or reverberation as a result of enhancement of speech intelligibility by such binaural advantages (Zurek, 1990).

The phenomenon of the BMLD may be related to the “cocktail party effect”, in which the discrimination of individual sounds in a complex acoustic environment is made easier if the
sound sources are separated in space (Yost, 1994, p. 182). The two phenomena may be related because in real situations, the interaural phase and level differences contributing to the BMLD only occur when the signal and masker are spatially separated (Moore, 1997, p. 239). However, not all signal-masker interaural differences that yield large BMLDs can be translated into real-life situations of spatial separation of sound sources. Moreover, the BMLD reflects the ability of our auditory system to detect the signal in noise, whereas the cocktail party effect refers to the locating and discriminating of sound sources. Therefore, the binaural processing and mechanisms underlying the two phenomena may differ.

Schoeny and Talbott (1994) suggest that peripheral hearing losses may have a profound effect on the size of the behavioural BMLD. It is reasonable to believe that listeners with conductive hearing loss may perform poorer in binaural processing than normal-hearing listeners or listeners with sensorineural hearing loss. This is because a large proportion of sound is transmitted to the cochleas by bone conduction for conductively impaired listeners (Bryne, Noble, & Ter-Horst, 1995). The interaural temporal and level difference cues arriving at the cochleas on both sides are thus greatly reduced. Children with a history of otitis media were reported to demonstrate smaller BMLDs compared with children with no history of otitis media (Gravel, Wallace, & Ruben, 1996; Moore, Hutchings, & Meyer, 1991). The poorer performance of the otitis media group may be associated with their difficulties in detecting and attending to signals in noisy environments (Moore et al., 1991).

Aging has also a detrimental effect on the behavioural BMLD. Pichora-Fuller and Schneider (1991, 1992, 1998) investigated the ability of elderly listeners, with early signs of presbyacusic hearing loss, to detect a 500-Hz signal in broadband noise in a number of dichotic conditions and compared it with that of young adults. They found that both groups demonstrated
behavioural BMLDs. Thresholds in diotic conditions were equivalent for both the presbyacusic listeners and the young listeners. However, thresholds in dichotic conditions were significantly higher for the presbyacusic listeners than for the young listeners. That is, a smaller behavioural BMLD was observed for the early presbyacusic listeners compared to the young listeners. Similar results were also obtained for elderly listeners with bilateral high-frequency sensorineural hearing loss and poor word-recognition performance (Novak & Anderson, 1982). Pichora-Fuller and Schneider (1992, 1998) hypothesize that a higher amount of temporal jitter as well as slowing in the speed of neural processing in the auditory system of early presbyacusic listeners interferes with the neural synchrony and thus binaural temporal processing of their auditory system. If so, the ability of the binaural system to detect signals in noise is compromised with advancing age. Such a decline may also affect the speech perception ability of presbyacusic listeners in noise (Grose, 1996).

Importantly, the behavioural BMLD is suggested to be one of the best indicators of early or subclinical auditory brainstem dysfunction not reflected by hearing thresholds (Hannley et al., 1983; Musiek & Lamb, 1992; Noffsinger et al., 1982; Noffsinger, Martinez, & Schaefer, 1985; Schoeny & Lamb, 1994). The behavioural BMLD has been demonstrated to be useful to study the central auditory function of multiple sclerosis patients, especially for the assessment of the auditory function of lower brainstem integrity (Musiek & Lamb, 1992; Schoeny & Lamb, 1994).

The behavioural BMLD is also proposed as a tool to diagnose lesions in sites other than the brainstem or VIIIth nerve in the central auditory pathways. Quaranta and Cervellera (1977) demonstrated that pathological (i.e., reduced) behavioural BMLDs were obtained for subjects with normal hearing but suffering from central nervous system diseases. They found that these patients, despite their normal hearing sensitivity to pure tones, also gave pathological test results
to both the time-compressed speech test and distorted speech test (Boca & Calearo, 1973).

Because these speech tests are indicative of central auditory lesions, Quaranta and Cervellera (1977) suggest that the behavioural BMLD is another means to diagnose central auditory pathway lesions. Similarly, Musiek and Lamb (1994) suggest that the behavioural BMLD may be used as a psychoacoustical measure for central auditory assessment to complement physiological measures such as the ABR.

The assessment of the behavioural BMLD may be included in a test battery for auditory processing disorder (APD) experienced by some school age children and adolescents. These students have normal hearing thresholds to pure tones but experience difficulty understanding speech in noisy, but not in quiet, situations (Chermak, Somers, & Seikel, 1998). The assessment of the behavioural BMLD may be used to assess the binaural processing ability of APD children and to investigate whether their auditory system is capable to integrate binaural cues normally (Lynn, Gilroy, Taylor, & Leiser, 1981; Noffsinger et al., 1985).

It has to be stressed, however, that the BMLD is not intended to distinguish between cochlear and retrocochlear lesions (Noffsinger et al., 1985). Moreover, unlike brainstem damage, damage in auditory cortical areas seems to have little or no effect on the behavioural BMLD (Lynn et al., 1981; Noffsinger et al., 1985).

**SUMMARY OF GENERAL FINDINGS OF THE BEHAVIOURAL BMLD**

The phenomenon of the BMLD has been widely studied. The differences of detectability of the various BMLD conditions are believed to be related to the fact that our auditory system is capable of making use of binaural cues to detect signals in noise, mainly the interaural temporal difference cues for low-frequency signals (Moore, 1997, pp. 237-238; Yost, 1994, pp. 123-125).
The binaural interaction model proposed by Jeffress has been extended to account for the mechanism underlying the behavioural BMLD by means of a cross-correlation model that incorporates the neuronal response pattern of the auditory system based on a cross-correlation estimated between the two signals arriving at the two ears at a specific interaural time delay (Colburn, 1973, 1977; Stern and Trahiotis, 1995). Nevertheless, not all BMLD conditions can be explained by Jeffress's model and the cross-correlation model. In addition, the detection of high-frequency signals in masker, which utilizes ILD instead of ITD and IPD, cannot be explained by the above models.

Studies of single cells in animal, and lesions and disorders in the human central auditory system, suggest that the behavioural BMLD is generated at the level of the lower brainstem, most probably at and above the level of the superior olivary complexes at which binaural auditory information converges from the two ears. The behavioural BMLD is suggested to be one of the best indicators of early or subclinical auditory brainstem dysfunction not reflected by hearing thresholds, as well as a means to assess auditory processing disorder. Unlike brainstem damage, however, damage in auditory cortical areas seems to have little or no effect on the behavioural BMLD (Lynn et al., 1981; Noffsinger et al., 1985). It is likely that the study of lesions may not be appropriate for the purpose of studying the BMLD. Instead, auditory processing and site of generation of these processes may be more suitable to define the BMLD. In addition, electrophysiological measures to derive the BMLD should be investigated as alternative methods for patients who are unable to perform behavioural tasks. In the following chapters, the use of transient auditory evoked potentials and the auditory steady-state responses (ASSRs) to study the BMLD will be reviewed, and a thesis study using the ASSR to explore the
generation site of and the mechanisms underlying the BMLD will be reported. First, a review on the ASSR will be presented.
CHAPTER 2:
AUDITORY STEADY-STATE RESPONSE
DEFINITION OF THE AUDITORY STEADY-STATE RESPONSE

In recent years, the auditory steady-state responses (ASSRs) have received considerable attention in evoked potential audiometry (Herdman & Stapells, 2001; John, Lins, Boucher, & Picton, 1998; Lins & Picton, 1995; Lins, Picton, & Picton, 1995; Lins, Picton, Boucher, Durieux-Smith, Champagne, Morgan, Perez-Abalo, Martin, & Savio, 1996; Picton, 1990; Picton, Durieux-Smith, Champagne, Whittingham, Morgan, Giguere, & Beauregard, 1998; Rance, Dowell, Rickards, Beer, & Clark, 1998; Suzuki, 2000; Tachisawa, 1997; Umegaki, 1995). The ASSR technique appears to be a promising method to predict the hearing thresholds of normal-hearing and hearing-impaired listeners of any age (Herdman & Stapells, 2001; Lins et al., 1995; Lins and Picton 1995; Lins et al., 1996; Picton et al., 1998; Rance et al., 1998).

Whereas transient auditory responses are evoked by transient auditory inputs, ASSRs are auditory evoked potentials (EPs) evoked by repetitive auditory inputs. A transient EP is evoked by the onset of each stimulus (tone burst or click) (Picton, 1990). Strictly speaking, after each response to each stimulus, there is a resting state before the neurons respond to the next stimulus (Regan, 1989, p. 34). Ideally, therefore, successive transient responses do not overlap each other in the time domain. A transient EP lasts for only a brief duration of time but the energy of the response extends approximately equally over a wide range of frequencies (Regan, 1989, pp. 34-35). Therefore, sharp peaks of transient EPs is best described in the time domain instead of the frequency domain. The transient EPs, when averaged to enhance the response signal-to-noise ratio, may give information on the system’s response to auditory inputs.

On the other hand, ASSRs are generated by a sufficiently fast stimulus rate such that the transient response to one stimulus overlaps the response to succeeding stimuli in the time domain (Picton, 1990). ASSRs are periodic responses with a constant phase relationship to the repeating
stimulus (Stapells et al., 1984). Regan (1989, p. 35) defined an idealized steady-state evoked potential as an EP whose constituent discrete frequency components remain constant in amplitude and phase over an infinitely long period of time. Thus, it is more convenient to describe ASSR in the frequency domain rather than the time domain. The frequency spectrum of the steady-state EP is concentrated into a discrete response centred on the repetition rate of the stimulus when the stimulus is presented above threshold (Lins et al., 1995; Lins and Picton, 1995; Picton et al., 1987; Rickards & Clark, 1984; Stapells et al., 1984).

GENERATORS OF THE ASSR

Amplitude Modulation Sensitivity within the Auditory pathway

In general, neurons throughout the auditory pathways are capable of encoding the amplitude modulation of signals with rate ranging from 20 Hz to up to 700-1000 Hz as a modulation of their discharge (Palmer, 1995). However, the modulation transfer function (MTF) shows that the neural sensitivity changes from the periphery to the cortex. The MTF is a plot of the degree of response modulation, or the total response, versus the modulation rate. The peak of the MTF is often referred to as the best modulation frequency. Studies of single cells in animals have shown that the best modulation frequencies in the cochlear nucleus varied from 80 to 700 Hz, depending on the different types of auditory nerve fibres involved (Palmer, 1995). However, MTFs of the units in the inferior colliculus show that the best modulation frequencies are generally lower than those in the cochlear nucleus, ranging from 30 to 500 Hz (Moller, 2000, pp. 205-222; Palmer, 1995). At the level of the auditory cortex, the best modulation frequencies of the majority of the neurons fall below 20 Hz (Palmer, 1995; Schreiner & Urbas, 1986).
Due to the differential sensitivity of amplitude modulation in the auditory pathways, it is reasonable to predict that the ASSRs to AM tones modulated at a low frequency (e.g., < 20 Hz) are likely to be related to the cortical sources. ASSRs to AM tones modulated at frequencies higher than 20 Hz may be related to auditory responses elicited below the cortical level, especially those greater than 70 Hz.

**Apparent Latencies of the ASSRs**

The site of generation of the ASSRs may be deduced from the transmission time of the EPs. According to Regan (1989, pp. 42-43), the transport time between the stimulation of the ear and the occurrence of the ASSR may be estimated from measurements of response phase. However, additional factors such as the rate of the stimulus, the slope of the phase-versus-frequency plot, the slope of the gain-versus-frequency plot, the phase shift between the stimulus and the response, and phase shift of unknown origin have to be considered in estimating the transport time. Due to the unattainability of some of the above factors and the difficulty in determining the transport time, Regan (1989, pp. 42-43) used the term "apparent latency" to describe the transport time assigned to each discrete frequency component. The apparent latency depends only on the rate of the stimulus, the slope of the phase-versus-frequency plot, and the number of harmonics. It has to be stressed that although the apparent latency has the same dimension as latency (i.e., time), they are qualitatively different (Regan, 1989, p. 43).

Phase of the ASSRs decreases in a linear fashion with the modulation frequency (MF) within certain frequency limits (Regan, 1972, pp. 76-82; Regan, 1984, pp. 42-43; Rickards & Clark, 1984; Stapells, Linden, Suffield, Hamel, & Picton, 1984). The apparent latency of the ASSR can be measured when the phase-versus-frequency plot is linear over a substantial range.
Recording ASSRs to tone-bursts presented at different stimulus rates, Stapells and colleagues found that the phase of the response increased linearly with the stimulus rate from 30 to 60/s (Stapells et al., 1984). The mean apparent latency then obtained is 34.0 ms, which lies within the range of the transient middle latency response wave Pa (Stapells et al., 1984). It is believed that the MF is the main factor that determines a particular ASSR apparent latency, which decreases with increasing MF (Rickards & Clarks, 1984).

Rickards and Clark (1984) recorded the ASSRs to amplitude-modulated tones with carrier frequencies varying from 250 to 8000 Hz, and MFs varying from 4 to 512 Hz. They found that, in the phase-versus-modulation frequency plot, three straight-line segments with abrupt changes of slope were observed at their intersections. In accordance with Regan’s suggestions, Rickards and Clark (1984) suggest that the linear relationship within specific modulation-frequency ranges (i.e., within each straight-line segment) indicates a constant latency of the measured response. This constant latency is the apparent latency of the ASSR described by Regan (1972, pp. 76-82). By means of regression analysis, Rickards and Clark (1984) outlined three discrete groups of ASSR apparent latencies according to the change of slope in the phase-versus-modulation frequency plot. Each group corresponds to a specific range of rate of the stimulus and is comparable to the latencies of the transient auditory evoked potentials. MFs of less than 20 Hz produce ASSRs with apparent latencies 60 ms and greater, corresponding to the transient slow cortical responses. MFs of 20-40 Hz produce ASSRs with apparent latencies 20-50 ms, corresponding to the transient middle latency (early cortical) responses. Finally, MFs of greater than 60 Hz produce ASSRs with apparent latencies shorter than 20 ms, corresponding to the transient VIIIth nerve and brainstem responses (Rickards & Clark, 1984).
By plotting the phase angles of the ASSR as a function of MF, Kuwada, Batra, and Maher (1986) found that the low-rate ASSR (25-55 Hz) showed a latency of about 31 ms whereas the high-rate ASSR (100-350 Hz) showed a latency between 7 and 9 ms. Kuwada and colleagues thus identified two separate generators for the low-rate ASSRs and high-rate ASSRs. Stapells and colleagues (1984) have found that the apparent latency of ASSR decreases with increasing tonal frequency (from 29.3 ms at 500 Hz to 20.3 ms at 4000 Hz) when tone-bursts are presented at a stimulus rate of 40/s. It is suggested that this decrease in apparent latency may be related to the velocity of the travelling wave along the basilar membrane (Stapells et al., 1984).

The 50-Hz ASSR recorded by Kuwada et al. (1986), using a 1000 Hz carrier frequency amplitude modulated at 50 Hz, shows an apparent latency (31.8 ms) very close to that of the 40-Hz response (37.2 ms) recorded by Picton, Skinner, Champagne, Kellett, and Maiste (1987), suggesting that the 40- and 50-Hz ASSRs may share the same site of generation. Picton and colleagues also suggest that the 40-Hz and 50-Hz responses elicited by amplitude-modulated (AM) tones might be very similar to the 40-Hz steady-state MLR elicited by rapidly presented tone bursts or clicks recorded by Galambos et al. (1981) and Stapells et al. (1984) (Picton et al., 1987).

Regan (1989, pp. 34-43) notes that it is possible that the three groups of apparent latencies may reflect the presence of three parallel subsystems within the auditory pathways. One of these subsystems is dominated for low MFs, another is dominated for intermediate MFs, and the third one is dominated for high MFs. The possibility of these three parallel auditory subsystems corresponding to different apparent latencies has not yet been well established (Regan, 1989, pp. 34-43).
ASSR Studies in Animals

Research with cats has suggested that the cochlear nucleus contributes to the generation of the ASSRs to AM tones modulated at 80 Hz. Suzuki obtained scalp-rewarded ASSRs evoked by AM tones modulated at 80 Hz in cats (Suzuki, 2000). Near-field potentials elicited by AM tones modulated at 80 Hz were also recorded from the ipsilateral cochlear nucleus and its vicinity. The phases of the 80-Hz ASSR were analyzed and used to produce a contour map. A rapid change in the phases recorded near the cochlear nucleus was observed in the contour lines, leading Suzuki to suggest that the ASSR to AM tones modulated at 80 Hz is generated within the cochlear nucleus in cats (Suzuki, 2000).

By recording the scalp-ASSR of unanesthetized rabbits, changes in the ASSR have been observed when the animal is under the influence of a series of drugs (Kuwada, Anderson, Batra, & Fitzpatrick, 2001). For instance, depressants attenuate the longer-latency ASSRs (previously found to be associated with low signal MFs) which also appear to have latencies similar to the shorter-latency ASSRs (previously found to be associated with high signal MFs). Kuwada and colleagues concluded that the scalp-recorded ASSR is a composite response from multiple brain generators (Kuwada et al., 2001). Consistent with previous findings, these researchers suggest that ASSRs to signals with MF less than about 60 Hz primarily reflect a contribution from the cortical generators. ASSRs to signals with MF at about 70-300 Hz reflect a contribution from a midbrain neural source, whereas ASSRs to signal with MF at greater than about 400 Hz reflect a contribution from a lower brainstem neural source (Kuwada et al., 2001).
Lesion Studies

The 40-Hz ASSR is suggested to be generated in the midbrain/thalamic area as supported by the fact that human patients with lesions in the midbrain/thalamic area show a change in the conduction time from the upper brainstem to the thalamus when 40-Hz clicks are used to evoke both the 40-Hz response and the transient ABR (Spydell, Pattee, & Goldie, 1985). Tachisawa (1997) reported that, for listeners with intracranial lesions, the amplitude of the 40-Hz ASSR and transient slow P1-N1 response is significantly decreased, even when the listeners are in an alert state. Tachisawa speculated that the 40-Hz ASSR and the transient slow P1-N1 potential may share the same site of generation in the auditory pathways. A similar site of generation of the transient middle latency response (MLR) is also suggested by scalp distribution analyses (Cohen, 1982) and studies of lesions in the temporal lobe (Kraus, Ozdamar, Hier, & Stein, 1982).

Magnetic and Electrical Source Analysis Studies

Magnetoencephalographic (MEG) study is a relatively new method to be used to trace the source of generation of the ASSR. Magnetic responses to stimuli modulated or presented at frequencies near 40 Hz suggest an active source in the region of the primary auditory cortex (Romani, Williamson, Kaufman, & Brenner, 1982). The recorded cerebral magnetic field of the ASSR to AM tones reveals that the ASSR amplitude decreases with increasing MF (from 10 Hz to 98 Hz). Analysis of the ASSR phase shows peaks of apparent latency of 72 ms for a 20-Hz MF, 48 ms for a 40-Hz MF, and 26 ms for a 80-Hz modulation frequency (Ross et al., 2000). These results are similar to the estimates by Rickards and Clark (1984).

Brain electrical source analysis can be carried out to localize the generators of the ASSR. By means of multi-channel recordings and varying the MF from 24 to 120 Hz, Mauer and Döring
(1999) reported that slow-rate ASSR has its source at both the cortical and brainstem level, whereas fast-rate ASSR (MF greater than 56 Hz) also originates from cortical and brainstem structures, but is dominated by the brainstem sources.

RECORDING AND ANALYSIS OF THE ASSR

**Stimulus**

ASSRs are elicited by fast repeating stimuli or by amplitude- or frequency-modulated pure-tones (carrier signal). Multiple stimuli may be used simultaneously to record the ASSRs (Herdman & Stapells, 2000; Lins & Picton, 1995; Lins et al., 1996). That is, pure-tones of different frequencies (at least one octave away from one another) amplitude-modulated at different rates and combined to form one stimulus may be used. The stimuli can be presented monaurally or binaurally, through air conduction or bone conduction.

The stimulus is generated digitally and then converted to analog form before presenting to the subjects. The timing of both stimulation and recording is exactly synchronized for the purpose of response detection during recording of the electroencephalographic signals (Johns et al., 1998) (see below). The stimulus is adjusted such that an exact integer number of both the carrier frequency and the MFs are present within a digital-to-analog (DA) buffer (Johns et al., 1998; Lins et al., 1996; Picton et al., 1998).

**Electroencephalogram (EEG) Recording**

According to Lins et al. (1996), for the purposes of threshold determination, the EEG is recorded by electrodes placed at the vertex, on the nape of the neck just below the hairline, and on the forehead (ground) for adults. The EEG is filtered, amplified, and sampled by an analog-to-
digital (AD) converter, and then fed into the computer for analysis. The rate of the AD conversion differs for different MF. In general, for lower MFs, the AD conversion rate is lower (John et al., 1998). The duration of each AD buffer exactly equals to the duration of each DA buffer used for stimulus generation (Picton et al., 1998).

The EEG signal recorded in each AD buffer is considered a “section” (Picton et al., 1998). An artifact rejection criterion is predetermined in the recording of the EEG to extract excessive noise from the steady-state EPs. A section is rejected if the potentials in the section do not meet the artifact rejection criteria. In order to allow reasonable artifact rejection, 16 sections are linked together to form a recording sweep (John et al., 1998; Picton et al., 1998). As mentioned above, the MFs of the stimulus are slightly modified so that each EEG recording sweep exactly contains an integer number of carrier frequency cycles within a recording section (Johns et al., 1998; Lins et al., 1996; Picton et al., 1998). In the method by Picton and colleagues, the EEG is recorded and averaged using a sweep consisting of 16 sections (Lins et al., 1996; Picton et al., 1998). The window of each section is about 1.02s. The duration of each averaged EEG sweep is thus about 16.38s. When the stimulus intensity is above threshold, a significant response (see below) is usually obtained after averaging 16 to 64 EEG sweeps (Lins et al., 1996).

ASSR Analysis

For the purpose of separating out the discrete frequency components of the response from background noise, the ASSR can be analyzed either by averaging the signal in the time domain or by increasing the duration of the data submitted to Fourier analysis (John et al., 1998). Fourier analysis is preferred to signal averaging because Fourier analysis is suggested to be a simpler and faster method (Regan, 1989, pp. 98-105; Rickards & Clark, 1984; Stapells et al., 1984). Fast
Fourier Transforms (FFTs) are now used to evaluate the ASSR online in a digital manner. By means of FFT, the time-domain waveforms are averaged in the frequency-domain based upon each EEG recording sweep (Lins et al., 1998). The frequency domain results can be expressed in a power spectrum, showing the response amplitude at different MFs, and polar plots, showing the amplitude and phase of the response at different MFs (Picton et al., 1998).

The degree of significance of the response is determined online by statistical methods, such as the F-statistic and/or $T^2$-statistic (Lins et al., 1996). The F-statistic evaluates whether the averaged response amplitudes at the MFs are different from the noise represented by the amplitudes in frequencies adjacent to the MFs (Lins et al., 1996). The F-statistic is the signal-to-noise ratio that compares the signal frequency power with the average power at the neighbouring frequency bins. For example, the F-ratio is computed between the response amplitude at the MF and the averaged amplitude in the 120 neighbouring frequency bins: 60 above and 60 below the MF (John et al., 1998). The F-ratio of the averaged waveforms is analyzed after every recording sweep in an accumulative manner. The significance of this F-ratio (expressed as a p-value) is estimated from the critical F-ratio and the degrees of freedom (Lins et al., 1996). Criteria for response present is usually set at $p < .05$.

The $T^2$-statistic evaluates the replicability of the response across all recording sections within a sweep. The response amplitude and phase at each MF are measured in each section within a sweep and the $T^2$ confidence limits are calculated (Lins et al., 1996; Picton et al., 1998). The degree of significance of the response can then be determined. It is reported that both the F- and $T^2$ statistics yield identical results (Picton et al., 1998). Therefore, either method can be used to track hearing thresholds.
STIMULUS EFFECTS OF THE ASSR

Types of Stimuli

Stimuli used to evoke ASSRs may include clicks (Galambos et al., 1981), tone bursts (Galambos et al., 1981; Stapells et al., 1984, 1987), amplitude-modulated (AM) tones (Herdman & Stapells, 2001; Lins & Picton, 1995; Lins et al., 1995; Lins et al., 1996; Picton et al., 1998; Rance et al., 1998), and frequency-modulated (FM) tones (Picton et al., 1987).

Stimulus Rate and Modulation Rate of Stimulus

When the rate of the stimulus increases from 10 to 30 Hz, the ASSR amplitude first decreases, then increases to a higher value, and then decreases again. When the stimulus rate is further increased, the ASSR amplitude will reach a maximum at a stimulus rate at 40/s, after which the amplitude will decrease (Stapells et al., 1984, 1987). Similar patterns of amplitude change were also reported by Kuwada et al. (1986) and Rickards and Clarks (1984). When the stimulus rate is above approximately 150 Hz, the ASSR amplitude drops precipitously to a much smaller value. The 40-Hz response is frequently observed superimposing onto the ABRs and MLRs during threshold measurement by using tone bursts or clicks at a rate of 40/s as stimuli (Galambos et al., 1981; Stapells et al., 1984; Stapells, Galambos, Costello, & Makeig, 1988). The amplitude of the auditory response is found to be highest at a stimulus rate of 40/s, whether signal averaging (Galambos et al., 1981; Stapells et al., 1984, 1987) or Fourier analysis (Stapells et al., 1984) is used to analyze the auditory responses. The 40-Hz steady-state potential may be considered as the steady-state MLR (Galambos & Makeig, 1992; Stapells et al., 1988) and may serve as a close approximation or prediction of the hearing thresholds of normal hearing listeners (Stapells et al., 1984; Stapells et al., 1987).
When AM or FM tones are used as the stimuli, the evoked ASSRs will have the same periodicity as the modulation rate of the stimuli, even though the stimuli contain no acoustic energy at the modulation frequency. Past studies have shown that the amplitude and phase of the ASSRs to AM or FM tones decrease with increasing the modulation frequency (Picton et al., 1987; Rickards & Clark, 1984). This relationship occurs not only with the first harmonic of the ASSRs, but also with the second harmonic (Rickards & Clark, 1984). Also, the higher the modulation rate, the shorter is the apparent latency of the ASSRs (Regan, 1989, pp. 42-43).

**Modulation Depth of AM and FM Tones**

The amplitude of the ASSR increases with increasing modulation depth (Ross et al., 2000) and appears to saturate at large modulation depths (Picton et al., 1987). However, the response phase does not change significantly with the modulation depth (Picton et al., 1987).

**Signal Frequency**

For the 40-Hz ASSR, both the response amplitude and the apparent latency decrease as the tone frequency increases (Galambos et al., 1981; Stapells et al., 1984). When AM tones are used as the stimuli, the ASSR threshold will give an estimation of the hearing threshold at the carrier frequency. In general, the ASSR amplitude decreases as the carrier frequency increases (Lins et al., 1996). However, the major factor that affects the ASSR amplitude, phase, and apparent latency is the modulation frequency of the stimulus (Rickards & Clark, 1984).

According to Lins et al. (1996), stimuli used in ASSR recording for the purpose of threshold determination are usually carrier tones of 500, 1000, 2000, or 4000 Hz, amplitude-modulated at a rate between 3 and 200 Hz. The modulation depth is usually kept at about 100%.
Picton et al. (1987) reported that the response amplitude is significantly larger for lower carrier frequencies (e.g., 500 Hz) for both AM and FM tones with modulation frequencies up to 54.7 Hz. Similar results are also found by Kuwada et al. (1986), with MF of 50 Hz and carrier frequencies varying between 250 to 8000 Hz.

**Stimulus Intensity**

For the 40-Hz ASSR, as the stimulus intensity decreases, the apparent latency of the ASSR increases (Regan, 1989; Stapells et al., 1984) whereas the ASSR amplitude decreases (Stapells et al., 1984). When 40-Hz AM or FM tones are used to evoke ASSRs, the response amplitude increases with the intensity of the stimulus (Lins et al., 1996; Picton et al., 1987; Ross et al., 2000) whereas the response phase decreases with increasing stimulus intensity (Picton et al., 1987).

**Subject Factors**

**Arousal State.** For ASSRs elicited by AM tones modulated at 40 Hz, the response amplitude recorded in the sleeping and sedation states is lower than that recorded in the awake state (Picton et al., 1987; Suzuki, 2000; Tachisawa, 1997). The threshold obtained for a 500-Hz tone with MF at 40 Hz in sleep state is higher than that obtained in the awake state (Umegaki, 1995). Except for the brainstem ASSR, which is likely evoked by AM tones modulated between 70-110 Hz, amplitudes of all ASSRs elicited by lower-rate and higher-rate AM tones are significantly reduced by drowsiness and sleep (Lins et al., 1996). Response amplitude of the 40-Hz ASSR may also fluctuate during different stages of sleep (Linden, Campbell, Hamel, & Picton, 1985), whereas brainstem ASSRs in infants and adults are not significantly affected,
whether the subject is awake, sleeping, or sedated (Lins et al., 1996; Lins & Picton, 1995; Rickards, Tan, Cohen, Wilson, Drew, & Clark, 1994). The signal-to-noise ratio of 80-Hz ASSR is reported to improve during sleep for adults (Levi, Folsom, & Dobie, 1993).

**Maturation Effect.** Large age-differences in the 40-Hz response have been reported between infants and adults (Levi et al., 1993; Stapells et al., 1988; Suzuki, 1984; Umegaki, 1995). In recording responses to clicks with rate varying from 10/s to 50/s, a prominent increase in the response amplitude was observed for normal-hearing adults at stimulus rates of 35/s and 40/s, whereas no amplitude increase was observed for normal-hearing infants and young children under the age of seven at the same stimulus rates (Suzuki, 1984). These young children demonstrated an increase in response amplitude at stimulus rate between 20/s and 30/s. At rates between 30/s and 50/s, the response amplitude decreased with increasing stimulus rate. Similar patterns were also observed using 1000-Hz tone bursts with stimulus rate varying from 10/s to 60/s (Stapells et al., 1988). No increase in response amplitude occurs at stimulus rate greater than about 20/s (Stapells et al., 1988).

Normal-hearing infants are also reported to demonstrate significantly smaller 40-Hz response than normal-hearing adults when the recording is carried out in sleep states (Levi et al., 1993; Umegaki, 1995). For AM tones with MFs between 50 and 80 Hz, however, the response amplitude for infants in sleep state increases with increasing stimulus rate (Levi et al., 1993). It has been suggested that the lower power of the 40-Hz response of infants is likely related to the delayed maturation of the 40-Hz ASSR generators, whereas the 80-Hz ASSR generators are relatively mature in infants and function like the adults’ (Levi et al., 1993).
SUMMARY OF GENERAL FINDINGS OF THE ASSR

ASSRs are auditory evoked potentials evoked by repetitive auditory inputs. They are generated by a sufficiently fast stimulus rate such that the transient response to one stimulus overlaps the response to succeeding stimuli in the time domain (Picton, 1990). The frequency spectrum of the ASSR is concentrated into a discrete response centred on the repetition rate of the stimulus (or its modulation rate) when the stimulus is presented above threshold (Lins et al., 1995; Lins and Picton, 1995; Picton et al., 1987; Rickards & Clark, 1984; Stapells et al., 1984). Multiple neuronal sources of the ASSR have been suggested. Analysis of the apparent latency of the ASSR, the differential sensitivity to amplitude modulation within the auditory pathway, source analysis results, and studies of lesions all suggest that ASSRs to stimulus with MF of less than 20 Hz may correspond to the transient slow cortical responses, ASSRs to stimulus with MF between 20 to 40 Hz may correspond to the transient middle latency (early cortical) responses, whereas ASSRs to stimulus greater than 60 Hz may correspond to the transient VIIIth nerve and brainstem responses (Kuwada et al., 1986, 2001; Rickards and Clarks, 1984; Ross et al., 2000; Spydell et al., 1985; Stapells et al., 1984).

ASSRs are elicited by fast repeating stimuli or by amplitude- or frequency-modulated pure-tones. The EEG is recorded and averaged using sweeps, each containing an integer number of carrier and modulation frequency cycles. Fast Fourier Transform (FFT) is used to evaluate the ASSRs online in a digital and objective manner. By means of FFT, the time-domain waveforms are averaged in the frequency-domain. The degree of significance of the response is determined either by comparing the averaged response amplitude to the amplitude of the adjacent noise frequencies (F-statistic) or by assessing the reliability of replicate responses ($T^2$-statistic) after
every sweep in an accumulative manner (Lins et al., 1996). The hearing thresholds can thus be tracked by these methods.

The response amplitude is generally larger for lower carrier frequencies (Picton et al., 1987) and increases with modulation depth (Ross et al., 2000). For adults, the ASSR amplitude reaches a maximum at a stimulus rate at 40/s, and decreases when the stimulus rates are greater than 40/s (Stapells et al., 1984, 1987). This response amplitude peak at 40/s is not observed for infants (Stapells et al., 1988; Suzuki, 1984). The amplitude of the 40-Hz response is reduced when the recording is performed in sleeping or sedation states (Picton et al., 1987; Suzuki, 2000; Tachisawa, 1997). The amplitude of the 80-Hz ASSR, however, is not significantly affected by the subject’s arousal state (Lins et al., 1996; Lins & Picton, 1995; Rickards, Tan, Cohen, Wilson, Drew, & Clark, 1994) or the subject’s age (Levi et al., 1993).

PRACTICAL APPLICATIONS AND ADVANTAGES OF THE ASSR

When AM tones are used to generate the ASSRs, the frequency content of the stimulus is concentrated at the carrier tone frequency and the two side-bands, with smaller spread of energy to other frequencies (Lins et al., 1996). Therefore, the stimuli are frequency-specific. Threshold assessment by means of ASSRs has proven to be an objective, effective, and reliable technique. The analysis of response is automatically generated and does not require subjective judgement of the presence of waves (Lins et al., 1996). ASSRs evoked by AM tones at modulation frequencies between 70 to 110 Hz have been shown to be a useful technique for the estimation of hearing thresholds in individuals with normal or impaired-hearing (Herdman & Stapells, 2001; Lins et al., 1995; Lins and Picton 1995; Lins et al., 1996; Picton et al., 1998; Rance et al., 1998). ASSRs are especially important because the technique allows more than one frequency (at more than one
modulation rate) to be evaluated simultaneously (Herdman & Stapells, 2001; Lins & Picton, 1995; Lins et al., 1996; Picton et al., 1998). This saves time in assessing an infant’s hearing and, at the same time, gives reliable results (Herdman & Stapells, 2001; Lins et al., 1996).

An additional advantage of the ASSR is that the stimuli used to evoke ASSRs are more readily processed by hearing aids and cochlear implants, since there are no abrupt changes over time and signal distortion is lessened (Lins et al., 1996; Picton, Durieux-Smith, Champagne, Whittingham, Morgan, Giguere, & Beauregard, 1998). Thus, the technique may be used to evaluate the performance of amplification devices in free field. It may also be used to assess the aided thresholds of individuals who are not able to provide reliable behavioural responses, such as infants, hearing-impaired children, and handicapped listeners (Picton et al., 1998). ASSRs might also be used to diagnose a cochlear from a retrocochlear defect, if the neural source for the generation of the slow-, medium-, and high-rate ASSR are known.

When used to describe the response of a linear system, the transient and steady-state EPs superimpose on each other and give the same information. However, if the system is nonlinear, as in the case of the auditory pathways and processing mechanisms, the transient EPs are not equivalent to the steady-state EPs, and they may reflect different information (Regan, 1989, pp. 34-42; Stapells et al., 1984). Although the MF is not represented in the stimulus waveform and carries no energy, it is registered by the auditory system and heard by the listener. This physiological and psychophysical phenomena may be attributed to the nonlinearity of the auditory system, which is captured by the ASSRs.

The ASSR may also be used as a tool to study psychophysical phenomena such as the BMLD. The behavioural BMLD is suggested to be one of the best indicators of early or subclinical auditory brainstem dysfunction not reflected by hearing thresholds, as well as a means
to assess auditory processing disorder (Hannley et al., 1983; Musiek & Lamb, 1992; Noffsinger et al., 1982; Noffsinger, Martinez, & Schaefer, 1985; Schoeny & Lamb, 1994). Using electrophysiological measures such as the ASSR to study the BMLD may help develop alternative assessment methods for patients who are unable to perform behavioural tasks. Studying the BMLD with the ASSR may also help explain why damage in auditory cortical areas seems to have little or no effect on the behavioural BMLD (Lynn et al., 1981; Noffsinger et al., 1985). To date, no agreement has been arrived on the generation site and the auditory processing mechanisms underlying the BMLD. It is hoped that, through electrophysiological measures, information reflected by the ASSR may complement that reflected by the transient evoked potentials, so that we may understand better the underlying auditory processing and site of generation of the BMLD.
CHAPTER 3:

ELECTROPHYSIOLOGICAL BMLD
STUDIES OF THE BMLD WITH AUDITORY EVOKED POTENTIALS

Over the past two decades, studies of the BMLD in normal-hearing listeners have been carried out using transient EPs, including the ABR, MLR, and the slow cortical auditory EPs (CAEPs). Signals used were brief tone frequencies of 580 Hz (Kevanishvili & Lagidze, 1987) or 500, 1000, 2000, and 4000 Hz (Fowler & Mikami, 1992a, b, 1995, 1996). So far, clicks have not been used as signals in the transient EP studies on the BMLD. Masker conditions have included both wideband (Kevanishvili & Lagidze, 1987; Fowler & Mikami, 1992a, b, 1995, 1996) and narrowband (Fowler & Mikami, 1992a, b, 1995, 1996) maskers. Usually, either the monotic ($S_mN_m$) or diotic ($S_0N_0$) condition served as the reference condition. BMLDs were calculated by subtracting the thresholds of dichotic conditions from the threshold of the reference condition. Dichotic conditions studied include $S_mN_0$, $S_0N_m$, $S_NN_m$ and $S_mN_0$.

Kevanishvili and Lagidze (1987) reported that the BMLD is seen in recordings of the CAEP (waves N1-P2) but not the ABR or the MLR. Using 580-Hz tone pulses as signals and continuous noise as the masker, Kevanishvili and Lagidze (1987) found that an average BMLD value of 10 dB was obtained with N1-P2 for the dichotic $S_NN_0$ condition.

Fowler and Mikami (1992a, b, 1995) also reported that the BMLD was only obtained using the slow auditory evoked potential (wave P2); no BMLD was derived by the ABR or the MLR. Using 500-Hz brief tones as signals and narrowband noise centred at 500 Hz as the masker, Fowler and Mikami (1992a) reported that the BMLD obtained for CAEP wave P2 was around 12 dB for the dichotic condition $S_NN_0$. They also reported that the BMLD increased with the noise level and was dependent on the bandwidth of the masker. Fowler and Mikami (1992b) found that the amplitude of CAEP (wave P2) BMLD for the dichotic condition $S_NN_0$ was larger for narrowbands of noise (50-Hz wide) than for more broadband noise (600-Hz wide), at least when
500-Hz tone-bursts were used as signals. Using similar diotic and dichotic stimuli as in the 1992 study, Fowler and Mikami (1996) report that a smaller P2-BMLD is obtained for the $S_\pi N_\pi$ condition (2 dB) while a much larger P2-BMLD is obtained for the $S_\pi N_o$ and $S_o N_\pi$ ($\sim$ 14 dB) conditions. Basically, the results are similar to the behavioural BMLD values reported by Hirsh (1948). However, no BMLD derived from the ABR is obtained using broadband noise as masker and tones of various frequencies (500 Hz, 1 kHz, 2 kHz, and 4 kHz) as signals (Fowler & Mikami, 1995).

In all the above studies by Fowler and Mikami (1992a, b, 1995, 1996), behavioural BMLDs were obtained, and these were positively correlated to the electrophysiological CAEP (wave P2) BMLDs. Because no ABR BMLD has thus far been observed, the mechanism underlying the BMLD may not be at the lower brainstem level. Instead, it has been speculated that the BMLD may be generated at the subcortical level immediately above the brainstem or even at the early cortical level (Kevanishvili and Lagidze, 1987). Fowler and Mikami (1996), however, found that no significant BMLD was obtained by the MLR (when 500-Hz brief-tones were used as signals and wideband noise was used as masker). The midbrain/thalamus, therefore, seems unlikely to be one of the generators of the BMLD.

Recently, Palmer et al. (1999) reported that, in the presence of fully correlated wideband noise, the overall discharge rate of the inferior colliculus neurons in guinea pigs was higher for the $S_\pi$ tone than for the $S_o$ tone. Palmer and colleagues also discovered that, in the presence of fully correlated signal, the $S_o$ signal was detectable at a lower level in $N_\pi$ noise than in $N_o$ noise in only 33 out of 62 neurons (Palmer et al., 1999). That is, about half the number of neurons in the brainstem that Palmer et al. (1999) studied are not sensitive to the detection of signal in the out-of-phase noise. Although this may be related to the absence of ABR BMLD for the dichotic $S_o N_\pi$
condition, it cannot explain why no ABR BMLD is demonstrated for the dichotic $S_N$ condition.

Based on the above ABR/MLR/CAEP results, the BMLD has been suggested to be generated at the cortical level and not at the brainstem level or the thalamus level (Fowler & Mikami, 1992, 1996; Kevanishvili and Lagidze, 1987). The brainstem and thalamus are nevertheless considered essential in maintaining and transmitting phase synchrony to higher levels of the auditory system (Fowler & Mikami, 1995). The electrophysiological findings, however, conflict with findings from studies of single cells in animals, and lesions and disorders in the human central auditory system, which suggest that the behavioural BMLD is generated at the level of the lower brainstem, most probably at and above the level of the superior olivary complex at which binaural auditory information converges from the two ears (discussed in Chapter 1).

Recently, Polyakov and Pratt (1998) found that shorter latencies and larger amplitudes of the binaural interaction components of the ABRs were obtained when noise was presented to mask click signals binaurally instead of monaurally. The binaural interaction components of the ABRs are determined by subtracting the binaurally evoked ABRs from the algebraic sum of the corresponding monaurally evoked ABRs in the presence of either ipsilateral monaural or binaural noise masking. Polyakov and Pratt (1998) suggested then that binaural processing and possibly BMLD processing were carried out in the human brainstem.

STUDY OF THE BMLD WITH THE ASSR: THE THESIS STUDY

To date, the phenomenon of the BMLD has not been systematically studied using the ASSRs. Previously, Galambos and Makeig (1992) recorded the 40-Hz ASSR of two subjects while presenting 500-Hz tone pips to one ear first ($S_m$), then adding broadband noise ipsilaterally
(S_mN_m) and contralaterally (S_mN_0), and finally adding the 500-Hz tone pips contralaterally (S_0N_0). No correlation was found between the perceptual BMLD and the 40-Hz amplitude change.

In the study of the present thesis, the ASSRs were used to derive the BMLD. The purpose is to investigate the brainstem and cortical mechanisms underlying the BMLD in humans. Past research on single cells in animals and lesions and disorders in the human auditory system concludes that the BMLD is generated at the brainstem level. However, as the review above indicates, results of studies of transient auditory EP BMLD in humans do not support this conclusion. The BMLD is only obtained by the slow CAEPs but not by the ABRs or the MLRs, thus it is then suggested that the BMLD is generated at the cortical level and not at the brainstem or thalamus level (Fowler & Mikami, 1992, 1996; Kevanishvili and Lagidze, 1987). It is also possible that the BMLD is generated at the brainstem level but is only manifested in the EPs generated above the brainstem, or the BMLD may be related to a system or generated from a pathway different from that of the ABR or MLR.

Although the transient and steady-state EPs are alternative formulations that describe the response of a linear system, they may give different information on the auditory pathways and processing mechanisms which behave nonlinearly (Regan, 1989, pp. 34-42). Due to the nonlinearity of the human auditory system, ASSRs may reflect aspects of the mechanisms underlying the BMLD that are not revealed by studies with the transient evoked potentials.

In the present study, 11 adult subjects with normal hearing were tested. The signals used were pure tones with carrier frequency at 500 Hz and 100% amplitude modulated at 80 Hz and 7(or13) Hz. ASSRs to 500-Hz stimuli which are amplitude modulated with a modulation rate of about 80 Hz are brain responses believed to originate from the brainstem auditory pathways, whereas ASSRs to 7(or13) Hz AM tones are believed to reflect auditory cortical processing.
(Kuwada, 1986; Kuwada, 2001; Mauer & Döring, 1999; Regan, 1984, pp. 42-43; Rickards & Clark, 1984; Ross et al., 2001; Stapells et al., 1984). Either a MF of 7-Hz or 13-Hz was used to elicit the cortical ASSRs so as to avoid the interaction of the cortical response with the individual’s α-activity which normally occurs with a frequency around 10 Hz (Regan, 1989, p. 37). The masker used was a 200-Hz-wide Gaussian noise centred at 500 Hz. The signal-masker combinations investigated included $S_o$, $S_oN_o$, $S_N$ and $S_oN_N$. Behavioural thresholds were determined in addition to ASSR thresholds, thus providing both the behavioural and ASSR BMLDs for the two rate regions for signal ($S_oN_o$ minus $S_N$) and noise ($S_oN_o$ minus $S_oN_N$) interaural phase reversal.

The relationship between the behavioural and ASSR BMLDs was determined in the current study. The ASSR BMLD results obtained in this experiment could then also be compared with the BMLD results obtained using the transient auditory EPs. Such a comparison may shed light on the pathways of brain processes underlying the BMLD with respect to the transient and steady-state EPs. Results may also reveal information on the generators for brainstem and cortical ASSR regarding the psychoacoustic phenomenon of the BMLD.
CHAPTER 4:

BRAINSTEM AND CORTICAL MECHANISMS

UNDERLYING THE BMLD IN HUMANS:

AN ASSR STUDY
INTRODUCTION

The binaural masking level difference (BMLD) is a psychoacoustic phenomenon that demonstrates how we benefit from using both ears instead of one when detecting signals in noise, especially when they are presented with an interaural phase or level difference. In the classic BMLD experiment, the threshold of a signal in noise is determined by presenting the signal (S) and noise (N) to one ear first, i.e., monaurally, which serves as the reference condition ($S_m N_m$, monotonic condition) (Hirsh, 1948; Jeffress, Blodgett, & Deatherage, 1952). The configurations (e.g., phase, intensity, duration, bandwidth, modulation, etc.) of the signal and/or noise are then manipulated at the two ears in various conditions and the masked threshold of the signal determined in each condition. The reduction (i.e., improvement) in the masked signal threshold in the various manipulated interaural conditions compared to that in the reference monaural case is referred to as the BMLD.

The masked threshold of a signal is the same in the monotonic condition ($S_m N_m$) as it is in the diotic condition ($S_0 N_0$, i.e., when the signal and noise are presented in phase binaurally) (Sever & Small, 1979), thus either the monotic or the diotic condition may be used as the reference condition to calculate the BMLD. A larger BMLD is obtained for low signal frequencies (McFadden and Pasanen, 1974), and when the polarity of either the signal or the masker is inverted (i.e., 180° out-of-phase) in one ear relative to the other in the dichotic conditions ($S_n N_o$ and $S_o N_n$) (Colburn & Durlach, 1965; Hirsh, 1948; Jeffress, Blodgett, & Deatherage, 1952). The value of the BMLD increases with increasing signal interaural level difference (Colburn & Durlach, 1965), with increasing masker intensity level (Durrant, Nozza, Hyre, & Sabo, 1984; Hirsh, 1948; McFadden, 1968), and/or with a more-narrow masker bandwidth (Bourbon and Jeffress, 1965; Wightman, 1970). A high degree of masker modulation...
may also facilitate the detection of signal in the $S_2N_0$ condition (Hall et al., 1998). The BMLD can be observed for other stimuli in addition to pure-tones, such as complex tones, clicks, and speech sounds (Moore, 1997, p. 237).

The differences of detectability of the various BMLD conditions are believed to be related to the fact that our auditory system is capable of making use of binaural cues to detect signals in noise, mainly the interaural temporal difference cues for low-frequency signals (Moore, 1997, pp. 237-238; Yost, 1997, pp. 123-125). Jeffress (1948) proposed a model to account for our ability to localize low-frequency sounds by using interaural time differences. In Jeffress’s model, there is a network of neurons, known as “coincidence detectors”, at the level of the midbrain that fire only when the inputs from the two ears reach the same neuron at the same time. A specific coincidence neuron will respond highest to inputs with a specific interaural time delay.

Jeffress’s model has been extended to account for the phenomenon of the BMLD by means of a cross-correlation model that incorporates the neuronal response pattern of the auditory system. For instance, Colburn (1973, 1977) and Stern and Trahiotis (1995) have presented a cross-correlation model in which a correlation between the two signals arriving at the two ears at a specific interaural time delay is established by the network of neurons as a function of the interaural time delay ($\tau$) and characteristic frequency (CF). The internal pattern of the output of a specific coincidence neuron that is activated by a specific interaural time delay is thus represented by such a correlation. After generating an estimate of the cross-correlation function of the instantaneous rate of the monaural fibres, the pattern of the neuronal response activity with respect to $\tau$ and CF is processed which determines the detectability of the signal in noise (Colburn & Durlach, 1978). The change in the pattern of output by the neural responses of the binaural
system from the monotic or diotic reference condition to the dichotic condition enables easy
detection of the signal, and hence the BMLD.

Auditory input information from both ears reaches the superior olivary complexes both
ipsilaterally and contralaterally, thus it is reasonable to suggest that the BMLD is generated at
and/or above this brainstem level (Moore, 1991). Past research on single cells in chinchilla
(Mandava, Rupert and Moushegian, 1996) and guinea pigs (Caird, Palmer, & Rees, 1991; Jiang,
McAlpine, & Palmer, 1997a, b; Palmer, Jiang, & McAlpine, 1999, 2000) and studies in humans
with central auditory processing disorders (Ferguson, Cook, Hall, Grose, & Pillsbury, 1998;
Gravel, Wallace, Ruben, 1996; Hannley, Jerger, Rivera, 1983; Noffsinger, Martinez, & Schaefer,
1982) suggest that the BMLD is processed at and above the level of the brainstem. However,
BMLD studies of transient auditory evoked potentials (EPs) in humans do not support this
conclusion. The BMLD is only obtained for the slow cortical auditory evoked potentials (waves
N1-P2) and not for the ABR or the MLR (Fowler and Mikami, 1992a, b, 1995, 1996;
Kevanishvili and Lagidze, 1987). These studies thus suggest that the BMLD is generated at the
cortical level and not the brainstem or thalamus level (Fowler and Mikami, 1992a, b, 1995, 1996;
Kevanishvili and Lagidze, 1987). Nevertheless, the brainstem and thalamus would be essential in
maintaining and transmitting phase synchrony to higher levels of the auditory system (Fowler &
Mikami, 1995). It is also possible that the BMLD is generated at the brainstem level but is only
manifested in the EPs generated above the brainstem, or the BMLD may be related to a system or
generated from a pathway different from that of the ABR or MLR.

In recent years, auditory steady-state responses (ASSRs) have received considerable
attention in evoked potential audiometry (Herdman & Stapells, 2001; John, Lins, Boucher, &
Picton, 1998; Lins & Picton, 1995; Lins, Picton, & Picton, 1995; Lins, Picton, Boucher, Durieux-
ASSRs are generated by a sufficiently fast stimulus rate such that the transient response to one stimulus overlaps the response to succeeding stimuli in the time domain (Picton, 1990). Regan (1989, p. 35) defined an idealized steady-state evoked potential as a response EP whose constituent discrete frequency components remain constant in amplitude and phase over an infinitely long period of time. The frequency spectrum of the steady-state evoked potential is concentrated into a discrete response centered on the repetition rate of the stimulus when the stimulus is presented above threshold (Lins et al., 1995; Lins and Picton, 1995; Picton et al., 1987; Rickards & Clark, 1984; Stapells et al., 1984). The ASSR technique appears to be a promising method to predict the hearing thresholds of normal-hearing and hearing-impaired listeners (Herdman & Stapells, 2001; Lins et al., 1995; Lins and Picton 1995; Lins et al., 1996; Picton et al., 1998; Rance, Dowell, Rickards, Beer, & Clark, 1998). Moreover, the analysis of the ASSR is automatically generated and does not require subjective judgement of the presence of waves. In addition, the stimuli used to evoke ASSRs are more readily processed by hearing aids and cochlear implants (Lins et al., 1996; Picton Durieux-Smith, Champagne, Whittingham, Morgan, Giguere, & Beauregard, 1998). Thus, the technique may be used to evaluate the performance of amplification devices in free field (Picton et al., 1998).

Data from the calculation of apparent latencies of the ASSRs (Rickards & Clark, 1984; Ross et al., 2000), studies of ASSR sources in cats (Suzuki, 2000), the differential amplitude modulation sensitivity along the auditory pathway (Palmer, 1995; Schreiner & Urbas, 1986), and magnetic and electrical source analysis studies (Ross, Borgmann, Draganova, Roberts, & Pantev,
2000) have suggested that ASSRs to amplitude modulated (AM) tones modulated at 80 Hz originate in the brainstem auditory pathways, ASSRs to 40-Hz AM tones originate in the thalamus or cortex level, while ASSRs to AM tones modulated at less than 20 Hz are believed to reflect auditory cortical processing.

Although the transient and steady-state EPs are alternative formulations that describe the response of a linear system, they may give different information on the auditory pathways and processing mechanisms which behave nonlinearly (Regan, 1989, pp. 34-43). Due to the nonlinearity of the human auditory system, ASSRs may reflect aspects of the mechanisms underlying the BMLD that were not revealed by studies with the transient evoked potentials. To date, the phenomenon of the BMLD has not been systematically studied with the ASSRs. In the present study, we recorded the ASSRs to derive the electrophysiologic BMLD. A 500-Hz signal 100% amplitude modulated at 80 Hz and 7(or13) Hz was used to elicit the brainstem and cortical ASSRs. The purpose of our study was to investigate the brainstem and cortical mechanisms underlying the BMLD in humans.

METHODS

Subjects

Eleven adult subjects (5 males; 6 females; mean age: 25.5 years) participated in this study. All subjects had normal hearing thresholds (i.e., ≤20 dB HL, re: ANSI, 1996) for both ears, as determined by the pure-tone audiometric testing at 500, 1000, 2000, and 4000 Hz. Normal middle-ear compliance and present acoustic reflexes at 500 and 1000 Hz for all subjects were confirmed by means of immittance measurement.
Stimuli, Maskers, and Conditions

Stimuli. The signals were sinusoidal tones with a carrier frequency of 500 Hz and 100% amplitude modulated at 7(or13) Hz and at 80 Hz. The AM tones were generated by the MASTER system (Multiple Auditory Steady-State Evoked Response) (John et al., 1998). Depending on the subjects' individual α-rhythm, typically around 10 Hz (Regan, 1989, p. 37), either the 7- or the 13-Hz AM tone was used to avoid the interaction of the cortical ASSR with the individual's α-activity. The intensity of all AM tones was kept constant at 60 dB SPL throughout the experiment. Acoustic calibration of the signal was checked daily.

Masker. The masker was a 200-Hz-wide noise centred at 500 Hz. The masker was produced by generating a broadband Gaussian noise (Tucker Davis Technologies WG1) and high-pass filtering with a cutoff frequency of 400 Hz (115 dB/octave attenuation slope) then low-pass filtering with a cutoff frequency of 600 Hz (115 dB/octave slope, Standard Research Systems SR650). It was further bandpassed between 400 and 600 Hz (Tucker Davis Technologies PF1). A relatively narrow bandwidth of noise was used because past research has shown that a more-narrow masker bandwidth produces a larger BMLD, both behaviourally (Bourbon and Jeffress, 1965; Wightman, 1970) and electrophysiologically (Fowler and Mikami, 1992b).

During threshold determination, the noise intensity was adjusted by an attenuator (Tucker Davis Technologies PA4) in order to mask the signal. The noise intensity 2 dB above the required level that just masked the signal was used as a representation of the signal threshold, which was used later to calculate the BMLD. Total power of noise before attenuation was maintained at 88 dB SPL. Acoustic calibration of the masker was checked daily.

Conditions. Four signal-masker conditions -- S_0, S_0N_0, S_πN_0, and S_0N_π -- were investigated for each of the two modulation frequencies (MFs). S_0 is the diotic condition in which only the
signal is presented, and the signal is presented to both ears, and is in-phase interaurally. \( S_o N_o \) is the diotic condition in which both the signal and the noise are presented to both ears and are in-phase interaurally, which serves as the reference condition. \( S_o N_o \) is a dichotic condition in which the signal is 180° out-of-phase in one ear and the noise is in-phase interaurally. Finally, \( S_o N_o \) is a dichotic condition in which the signal is in-phase interaurally and the noise is 180° out-of-phase in one ear. The polarity inversion of the stimuli and masker was accomplished by using the Tucker Davis Technologies SM3 module. The four signal-noise conditions were presented using ER-3A insert earphones.

**Electroencephalogram (EEG) Recording**

Three recording electrodes were placed on a subject’s forehead (ground), the left ear-lobe (inverting), and the vertex (non-inverting). Inter-electrode impedance was kept at or below 3 kOhms throughout the experiment.

For the cortical ASSR to the 7(or13)-Hz AM stimuli, the EEG was filtered between 1 and 30 Hz (12 dB/octave slope) and amplified 40,000 times. Artifact rejection level was set at ±100 \( \mu \)V. For the brainstem ASSR to the 80-Hz AM stimuli, the EEG was filtered between 30 and 250 Hz (12 dB/octave slope) and amplified 80,000 times. The artifact rejection level was set at ±40 \( \mu \)V. The EEG was recorded and averaged using a sweep consisting of 16 sections (Lins et al., 1996; Picton et al., 1998). The window of each section was 1.02s. The duration of each averaged EEG sweep was thus 16.38s. The MF of the stimulus were adjusted so that each EEG recording sweep contained an exact integer number of carrier frequency and MF cycles (Johns et al., 1998; Lins et al., 1996; Picton et al., 1998). When above threshold, a significant response (see below) was usually obtained after averaging 24 to 48 EEG sweeps (previously found in a pilot study,
Appendix C). The amplification of the recording system (EEG and MASTER system) was calibrated daily.

ASSR Analysis

Fourier analysis was used to analyze the ASSRs so as to separate out the discrete frequency components of the response. Fast Fourier Transform (FFT) was used to evaluate the ASSRs online in a digital manner. By means of FFT, the time-domain waveforms were averaged in the frequency-domain based upon each EEG recording sweep that lasted 16.38 s. The ASSR amplitude and phase were quantified and the degree of significance of the response was determined online by an analysis of the variance (F-statistic) of the FFT (Lins et al., 1996). The averaged response amplitude at the MF was compared to the noise amplitude at frequencies adjacent to the MF. The signal-to-noise F-ratio was computed between the response amplitude at the MF and the averaged amplitude in the 120 neighbouring frequency bins: 60 above and 60 below the AM frequency, extending about 5 Hz on each side of the MF. The F-ratio (expressed as a p-value) of the averaged waveforms after every sweep was analyzed by the MASTER system in an accumulative manner (John et al., 1998). The significance of this F-ratio was evaluated against critical values for F at 2 and 240 degrees of freedom (Lins et al., 1996). The criteria for a “present response” was set at p-value < .01, which was maintained for at least four consecutive sweeps. Criteria for “no response” was set at p-value ≥ .30 and/or if the response amplitude was smaller than the noise after completing 48 sweeps.
Procedure

Subjects participated in two sessions for this study, with each session lasting about 2-3 hrs. Before the first session, immittance measurement and hearing screening were administered to each subject to ensure normal hearing thresholds and normal middle-ear function. Behavioural and ASSR masked thresholds of each of the two AM tones were determined for the reference condition (i.e., \( S_oN_o \)) and the two dichotic conditions (i.e., \( S_oN_o \) and \( S_oN_n \)). Thresholds of a total of 12 conditions were thus determined for each subject. Behavioural masked thresholds were obtained first in the first session of the experiment. For both the behavioural and ASSR procedures, the test order of the two AM tones was randomly determined. In both procedures, however, the signal-only diotic condition (i.e., \( S_o \)) was always presented first before the other three signal-masker conditions, the presentation order of which was randomized. This was performed in order to ensure responses present and to determine if cortical ASSRs were contaminated by the subject’s α-activity.

Behavioural BMLD. Subjects were seated in a double-walled sound attenuating room and asked to press a button as long as they hear the AM tone through the ER-3A earphones. The signal-only diotic condition (i.e., \( S_o \)) at 60 dB SPL for the first AM rate was presented to the subjects first so that they would become familiar with the signal. The first randomized signal-masker condition was then presented. The signal was kept at 60 dB SPL for all signal-masker conditions. The masker level was attenuated by the 4-dB-down 2-dB-up staircase procedure until the signal was just masked by the masker in two attempts out of three. Two dB above this masker level was set as the threshold of the AM tone in this signal-masker condition. Thresholds in the other two randomized signal-masker conditions were determined in the same way. After the thresholds of the reference condition and the two dichotic conditions were determined for the first
AM rate, the same threshold determination procedures were proceeded to the other AM rate. The
behavioural BMLDs for each AM tone were calculated by subtracting the masked thresholds in
the dichotic conditions from that in the reference condition, respectively.

**ASSR BMLD.** ASSR thresholds were determined after the behavioural thresholds were
obtained. Subjects were seated in a reclining chair in the double-walled sound attenuating room.
In the first session of the experiment, each subject was presented with a 7-Hz AM signal (S₀) and
ASSRs recorded. If response was “present” and not interfered by the subject’s α-activity, the 7-Hz
AM tone was used to evoke the subject’s cortical ASSRs for the ASSR recording of the
experiment. If “no response” was evoked by the 7-Hz AM signal, the 13-Hz AM signal was
attempted. If the subject did not give “present response” to both the 7-Hz and 13-Hz signals,
he/she was discharged from the study. The order of recording of the 7- or the 13-Hz (cortical) and
80-Hz (brainstem) ASSRs was then randomized.

During the 7(or13)-Hz AM stimuli recording, subjects either read or watched closed-caption videos quietly. They were not allowed to sleep because past research has shown that
ASSRs to tones modulated at a rate below 70 Hz may be significantly affected by sleep (Lins et
al., 1996; Lins & Picton, 1995; Rickards et al., 1994). During the 80-Hz AM stimulus recordings,
subjects either watched closed-caption videos quietly or were allowed to sleep. Similar to the
behavioural testing, the order of presentation of the three signal-masker conditions (i.e., S₀N₀,
S₀Nₓ, and S₀Nₓ) was randomized for the ASSR recording.

The signal-only diotic condition (i.e., S₀) at 60 dB SPL for the first randomized AM
stimulus was always presented first to ensure a significant ASSR from the subject. The signal was
kept at 60 dB SPL in all signal-masker conditions. The first randomized signal-masker condition
was then presented. The starting masker level began at 20 dB SPL lower than that required for the
behavioural threshold for the same condition. This starting noise level was determined from pilot studies which indicated that a lower noise level was required to just mask the signal for the ASSR thresholds compared to the behavioural thresholds (Appendix C). The noise level was adjusted to achieve both "present response" and "no response" to the signal by a 4-dB-down 2-dB-up or 4-dB-up 2-dB-down method. The noise level at which the signal was just masked by the noise was recorded. Two dB above this masker level was set as the threshold of the AM tone in this signal-masker condition. Thresholds in the other two randomized signal-masker conditions were determined in the same way.

After the ASSR thresholds of the reference condition and the two dichotic conditions were determined for the first AM stimulus, the same threshold determination procedures were carried out for the second AM stimulus. The ASSR BMLDs for each AM tone were calculated by subtracting the masked thresholds in the dichotic conditions from that in the reference condition, respectively.

Data Analysis

For each AM stimulus, the ASSR and behavioural BMLDs (in dB) were calculated by subtracting the ASSR and behavioural thresholds of the dichotic conditions (i.e., SₐN₀ and S₀Nₐ) from that of the reference condition (i.e., S₀N₀), respectively. In order to evaluate the effect of AM rate, behavioural or ASSR mode, and signal/noise polarity inversion on the value of the BMLD, a 3-way repeated-measures analysis of variance (ANOVA) was carried out. Differences were considered significant at p < .05. The effect of AM rate and signal/noise polarity inversion on the behavioural BMLD was further evaluated by performing a 2-way ANOVA. In order to determine whether the SₐN₀-ASSR-BMLDs differed from S₀Nₐ-ASSR-BMLDs, and whether brainstem (80-
Hz) ASSR BMLDs differed from cortical (7- or 13-Hz) ASSR BMLDs, t-tests for dependent samples (two-tail) were performed. Finally, the correlation between the behavioural and ASSR BMLDs was evaluated using Pearson product-moment correlation coefficients.

RESULTS

Behavioural BMLD

The means and standard deviations (SD) of the behavioural masked thresholds of the two AM stimuli in the reference condition ($S_0N_0$) and the two dichotic conditions ($S_\pi N_0$ and $S_0N_\pi$) for the 11 subjects are presented in Table 1. The means and standard deviations of the behavioural BMLDs are also tabulated. Individual behavioural thresholds and BMLDs are tabulated in Appendix A. Signal level (60 dB SPL) was constant throughout the experiment, thus thresholds of the masked signal in Table 1 are those masker values (in dB SPL) 2 dB above the masker level that was required to just mask the signal.

| Table 1. Behavioural thresholds (expressed as noise levels in dB SPL) and BMLDs (in dB). |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
|                                 | Modulation Frequency            | Dotic Stimulus                  | Dichotic Stimulus               | Dichotic Noise                  |
|                                 |                                 | $S_0N_0$                        | $S_\pi N_0$                     | $S_0N_\pi$                      | BMLD                           |
| 7(or13) Hz                      | mean                            | 66.9                            | 76.2                            | 9.3                             | 75.6                           | 8.7                            |
|                                 | SD                              | 6.3                             | 5.6                             | 2.6                             | 6.7                            | 1.8                            |
| 80 Hz                           | mean                            | 67.1                            | 75.6                            | 8.5                             | 77.6                           | 10.5                           |
|                                 | SD                              | 3.4                             | 3.4                             | 2.0                             | 4.6                            | 2.4                            |

For both AM stimuli, the masked threshold in the $S_0N_0$ condition was much higher than that in the $S_\pi N_0$ and $S_0N_\pi$ conditions. That is, a large behavioural BMLD (mean = 8.5-10.5 dB)
was obtained for both MFs when either the signal or the noise was 180° out-of-phase between the ears. For the 7(or13)-Hz stimuli, the behavioural BMLD obtained when the signal phase was inverted in one ear is slightly larger than that obtained when the noise phase was inverted in one ear. For the 80-Hz stimuli, however, the behavioural BMLD obtained when the noise phase was inverted in one ear is slightly larger than that obtained when the signal phase was inverted in one ear. The 2-way ANOVA, however, reveals that the behavioural BMLDs obtained in the two dichotic conditions (df = 1, 10; F = 2.664, p = .134) for the two AM frequencies (df = 1, 10; F = .019, p = .892) do not differ significantly from one another.

ASSR BMLD

Figure 1 depicts the FFTs of ASSRs to the 500-Hz pure-tone amplitude modulated at 13 Hz (Fig. 1a) and 80 Hz (Fig. 1b) for one subject in the four signal-masker conditions. The MFs of the signal were adjusted to 12.695 Hz and 80.078 Hz respectively so that each EEG recording sweep contained an exact integer number of carrier frequency and MF cycles. For this subject, both cortical (13 Hz) and brainstem (80 Hz) ASSRs were obtained in the signal-only condition (S₀). At a masker level of 54 dB SPL, cortical ASSRs were obtained in the dichotic conditions (S₀N₀ and S₀N₀) but not in the diotic condition (S₀N₀). Similar results were obtained for the brainstem ASSRs at a masker level of 62 dB SPL.

The means and standard deviations of the ASSR masked thresholds of the two AM stimuli in the reference condition (S₀N₀) and the two dichotic conditions (S₀N₀ and S₀N₀) for the 11 subjects are presented in Table 2. The means and standard deviations of the ASSR BMLDs are also tabulated. Individual ASSR thresholds and BMLDs are tabulated in Appendix B. As shown in Table 2, only the cortical ASSRs (7 or 13 Hz) demonstrated BMLDs, and these were found
Figure 1a. FFTs of ASSRs to 500-Hz sinusoids amplitude modulated at 12.695 Hz for one subject. Signal level = 60 dB SPL, Masker level = 54 dB SPL. The arrow indicates 12.695 Hz. Significance of response is also indicated.

So

![Power Spectrum](image1)

SoNo

![Power Spectrum](image2)

S\pi No

![Power Spectrum](image3)

SoN\pi

![Power Spectrum](image4)

Present response: $p < .01$
Figure 1b. FFTs of ASSRs to 500-Hz sinusoids amplitude modulated at 80.078 Hz for one subject. Signal level = 60 dB SPL, Masker level = 62 dB SPL. The arrow indicates 80.078 Hz. Significance of response is also indicated. Electric line noise is present at 60 Hz and its harmonic at 120 Hz.

Present response: $p < .01$.
only when the signal phase was inverted in one ear ($S_nN_o$) but not when the noise phase was inverted ($S_oN_n$). No BMLD was obtained for brainstem ASSRs (80 Hz) when either the signal or noise was inverted in one ear.

Table 2. ASSR thresholds (expressed as noise levels in dB SPL) and BMLDs (in dB).

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Modulation Frequency</th>
<th>Diotic Stimulus</th>
<th>Dichotic Stimulus</th>
<th>Dichotic Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$S_oN_o$</td>
<td>$S_nN_o$</td>
<td>BMLD</td>
</tr>
<tr>
<td>7(or13) Hz</td>
<td>mean</td>
<td>47.8</td>
<td>53.6</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>8.3</td>
<td>5.7</td>
<td>5.6</td>
</tr>
<tr>
<td>80 Hz</td>
<td>mean</td>
<td>61.8</td>
<td>62.7</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>SD</td>
<td>6.6</td>
<td>3.8</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Two-tail t-tests for dependent samples were performed to investigate the ASSR BMLDs. When the signal phase is inverted, the cortical ASSR BMLD is significantly larger than the brainstem ASSR BMLD ($t = 3.151; \text{df} = 10; p = .010$). However, when the noise phase is inverted, neither ASSR shows a BMLD, thus the cortical ASSR BMLD does not differ significantly from the brainstem ASSR BMLD ($t = 0.323; \text{df} = 10; p = .752$). The result of t-test analysis of only the cortical ASSR BMLDs shows that the cortical ASSR BMLD obtained when the signal phase was inverted is significantly larger than that obtained when the noise phase was inverted ($t = 2.39; \text{df} = 10; p = .038$).

Comparison Between Behavioural and ASSR BMLDs

Behavioural and ASSR BMLDs in the various signal-masker conditions are summarized in Table 3. Results of the 3-way repeated-measures ANOVA are illustrated in Table 4. As shown
in Table 3, all behavioural BMLD mean values are higher than the ASSR counterparts, as indicated by the significant main effect for behavioural vs ASSR mode (Table 4). That is, the mean behavioural BMLD across the two dichotic conditions for the two MFs (9.3 dB) is significantly larger than the ASSR counterpart (2.3 dB). There is also a significant main effect for AM rate, such that the mean 7(or13)-Hz BMLD for both the behavioural and ASSR modes and for both signal and noise polarity inversion (6.3 dB) is significantly larger than the 80-Hz counterpart (5.2 dB).

**Table 3.** Comparison of behavioural and ASSR BMLDs (in dB).

<table>
<thead>
<tr>
<th>Condition</th>
<th>7/13-Hz AM tones</th>
<th>80-Hz AM tones</th>
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<td>S₀N₀-SₓN₀</td>
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**Table 4.** Results of the 3-way analysis of variance for the effects of AM rate (RATE), behavioural vs ASSR mode (MODE), and signal vs noise polarity inversion (INVERSION).

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<tr>
<td>MODE</td>
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<td>49.09</td>
<td>&lt; .000*</td>
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<td>RATE x MODE</td>
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<td>MODE x INVERSION</td>
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<tr>
<td>RATE x MODE x INVERSION</td>
<td>1, 10</td>
<td>1.41</td>
<td>0.263</td>
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</table>

df = degree of freedom  
* = significant at p < .05  
† = nonsignificant trend at p ≤ .1
A significant interaction is obtained between effects of behavioural vs ASSR mode and signal vs noise polarity inversion, such that the significantly larger BMLD obtained when signal polarity is inverted compared to when noise polarity is inverted only occurs for the ASSR results and not the behavioural results.

A nonsignificant trend is obtained between the effects of AM rate and behavioural vs ASSR mode, such that the 7(or13)-Hz BMLD is larger than the 80-Hz BMLD for the ASSR results only. This finding is supported by the 2-way ANOVA for the behavioural BMLD which shows that there is no significant difference among the behavioural BMLDs obtained in the two dichotic conditions for the two MFs. Another nonsignificant trend is obtained between the effects of AM rate and signal vs noise polarity inversion, such that the cortical ASSR (7 or 13 Hz) BMLD is larger than the brainstem ASSR (80 Hz) BMLD when the signal polarity is inverted at one ear but not when the noise polarity is inverted. The t-test analysis for the ASSR BMLD presented above demonstrates that the cortical ASSR BMLD does not differ significantly from the brainstem ASSR BMLDs when the noise phase is inverted.

The correlations between the behavioural and ASSR BMLDs for the two AM tones measured by Pearson product-moment correlation coefficients are presented in Table 5. All correlations failed to reach significance (i.e., p > .05), indicating no association between the behavioural and ASSR BMLDs obtained in the present study.

Table 5. Correlation coefficients between behavioural and ASSR BMLDs

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<th>80-Hz AM tones</th>
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<td>$S_{p}N_{o}$-BMLD</td>
<td>-0.43$^{\text{NS}}$</td>
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<td>$S_{p}N_{o}$-BMLD</td>
<td>0.47$^{\text{NS}}$</td>
<td>0.23$^{\text{NS}}$</td>
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</table>

$^{\text{NS}}$ = not significant (p > .05)
DISCUSSION

Behavioural BMLD

Behavioural BMLDs (mean = 8.5-10.5 dB) are present for both modulation rates and for both signal and masker phase changes. No previous study of the behavioural BMLD using AM tones as stimuli is available for comparison to the data found in the present study. However, the behavioural BMLD values found in the present study using AM tones are comparable to the results from past studies using low-frequency pure-tones as stimuli (Durlach and Colburn, 1978; Hirsh, 1948; Jeffress et al., 1952; Kohlrausch, 1986; Moore, 1997, pp. 237-238). Past studies have indicated that the behavioural BMLD obtained with low-frequency signals and broadband noise is largest for the condition $S_o N_o$ ($\sim$ 15 dB), followed by the behavioural BMLD for the condition $S_o N_{\pi}$ ($\sim$ 13 dB) (Hirsh, 1948; Moore, 1997, pp. 237-238). In the present study, there is no difference in BMLDs for 7(or13)-Hz versus 80-Hz AM tone, or for condition $S_o N_o$ versus $S_o N_{\pi}$.

ASSR BMLD

In contrast to the behavioural results, only the cortical ASSRs (7 or 13 Hz) demonstrate BMLDs, and these are found only when the signal phase is inverted in one ear but not when the noise phase is inverted. No BMLD is obtained for the brainstem ASSRs (80 Hz) when either the signal or noise is inverted in one ear. The mean cortical ASSR BMLD obtained when the signal phase is inverted is 5.8 dB. No previous study on the BMLD derived by ASSRs is available for comparison with the data found in the present study.
Comparison between Behavioural and ASSR BMLDs

The ASSR BMLDs obtained are significantly smaller than the behavioural BMLDs. Whereas the behavioural BMLDs do not differ significantly from one another, a significant effect of AM rate and signal/noise polarity inversion is observed for ASSR BMLDs. Only the cortical ASSRs (7 or 13 Hz) demonstrate BMLDs, and only when the signal phase is inverted in one ear and not when the noise phase is inverted.

The lack of correlation between the behavioural and ASSR BMLDs may indicate no association between the two modes. It is also possible that nonsignificant correlations are obtained in the present study because of the restricted range of BMLDs in this small subject sample.

Comparison between ASSR and Transient Evoked Potential BMLDs

AM tones modulated at 80 Hz are brain responses believed to originate from the brainstem auditory pathways; ASSRs to 7(or13)-Hz AM tones are believed to reflect auditory cortical processing (Rickards & Clark, 1984; Ross et al., 2000; Suzuki, 2000). Results of this experiment are similar to the pattern of results previously found for the transient ABRs and the N1-P2 CAEPs (Fowler & Mikami, 1992a, b, 1995, 1996; Kevanishvili & Lagidze, 1987). In those studies, significant BMLDs (10-14 dB) were found for the transient cortical N1-P2 response, but not for the middle latency and brainstem responses. In the present experiment, no BMLD is obtained for the brainstem ASSRs (80 Hz) (mean = 0.9 dB), but a clear BMLD is obtained for the cortical ASSRs (7 or 13 Hz). This may indicate that the behavioural BMLD is due to auditory processing up to and including the cortical level. Alternatively, it may also suggest that brain processes underlying the behavioural BMLD may occur either in a different pathway (or different
neuronal groups) or beyond the brainstem auditory processing reflected by the 80-Hz ASSRs. It is also possible that the BMLD is generated at the brainstem level but is only manifested in the EPs generated above the brainstem.

Results of the present study differ from previous research in that the cortical ASSRs show a BMLD when there is a change of the signal interaural phase (mean = 5.8 dB), but not for a change of the noise interaural phase (mean = 1.5 dB). In the earlier studies, the N1-P2 BMLD was obtained for both signal and noise inversion conditions (Fowler & Mikami, 1992a, b, 1995, 1996; Kevanishvili & Lagidze, 1987). These results suggest that the cortical ASSRs (7 or 13 Hz) are not directly related to the slow cortical transient N1-P2 responses. That is, the generator of the cortical ASSR is likely different from the generator of the cortical transient N1-P2 responses.

Further, the positive correlation found previously between the behavioural BMLD and N1-P2 CAEPs (Fowler & Mikami, 1992a, b, 1996; Kevanishvili & Lagidze, 1987) does not occur between the behavioural BMLD and the cortical ASSR. The cortical ASSR BMLD (mean = 5.8 dB) is also smaller compared to the behavioural BMLD (mean = 9 dB) found in the present study, as well as the cortical transient BMLD (10-14 dB) reported in previous studies (Fowler & Mikami, 1992a, b & 1995; Kevanishvili & Lagidze, 1987), and as indicated above, no cortical ASSR BMLD is obtained for a change in the noise interaural phase. These differences suggest that the ASSR BMLD may reflect processes that are, at least partially, different from those underlying the behavioural BMLD, as well as processes that are different from those represented by the transient evoked potentials. It may also be hypothesized that the generator for the slow cortical transient N1-P2 responses is related to the behavioural S<sub>0</sub>N<sub>-</sub>-BMLD that is not reflected by the cortical ASSR.
Results of the present study suggest that the cortical (7 or 13 Hz) ASSRs may reflect the output of neural populations which previous research has shown to be sensitive to binaural differences in signal but insensitive to binaural differences in noise (Palmer et al., 1999). Palmer et al. (1999) investigated the neuronal discharge of cells within the inferior colliculus of guinea pigs in response to signals in noise with different interaural phase relationships. In the presence of a fully correlated wideband noise \( N_0 \), the overall discharge rate of the neurons was higher for the \( S_a \) tone than for the \( S_o \) tone. In the presence of a fully correlated signal \( S_o \), however, the signal was detectable at a lower intensity level in \( N_a \) noise than in \( N_o \) noise in only 33 out of 62 neurons (Palmer et al., 1999). That is, about half the number of neurons in the brainstem that Palmer et al. (1999) studied are not sensitive to the detection of the \( S_o \) signal in the \( N_a \) noise.

In contrast to the cortical ASSR, the cortical transient EPs reflect the behavioural BMLD obtained for both signal and noise phase changes. These results lend to the hypothesis that, in contrast with signal phase change, binaural information about noise phase change is transmitted by a different neuronal substrate and/or along a different pathway to the cortical level.

Future Studies

Further investigation of the auditory pathways intermediate to the brainstem and cortical levels using the ASSR (e.g., using a 40-Hz AM stimuli) may be of value to compare to the transient MLR results. If no middle-latency ASSR BMLD is obtained, it might indicate that auditory processing underlying the behavioural BMLD occurs beyond the thalamic level. If, on the other hand, a middle-latency ASSR BMLD is obtained, auditory processing underlying the behavioural BMLD may take place in a pathway that is not reflected by the transient MLRs (Fowler & Mikami, 1996; Kevanishvili & Lagidze, 1987). Additionally, investigation of the
effects of signal vs noise polarity inversion on the middle-latency ASSR BMLD may reveal additional information on the neuronal sensitivity to phase changes along the thalamo-cortical auditory pathways.

Further, investigations of ASSR amplitude and phase changes with various signal-masker conditions may reveal new information concerning the ASSR BMLD, the main effects for AM rate and signal vs noise polarity inversion, as well as new information on the interactions between these effects. Finally, expansion of the subject sample size as well as inclusion of subjects with a wide range of BMLDs may reveal a stronger association between the behavioural and ASSR BMLDs.

Conclusion

The behavioural BMLD values found in the present study using AM tones with a low-frequency carrier are comparable to the results from past studies using low-frequency pure-tones as stimuli. The behavioural $S_n N_o$-BMLD and $S_o N_n$-BMLD found in the present study are not significantly different from each other. In contrast with the behavioural results, no BMLD is obtained for brainstem ASSRs (80 Hz), whereas for cortical ASSRs (7 or 13 Hz), a BMLD is only demonstrated when the signal phase is inverted in one ear but not when the noise phase is inverted. The ASSR BMLDs obtained are significantly smaller than the behavioural BMLDs.

Binaural processing of afferent auditory input is believed to commence at the level of the superior olivary complexes. Past research on single cells in animals and lesions in the human auditory system suggests that the behavioural BMLD is processed at and above the level of the brainstem. However, results of the present study suggest that the brain processes underlying the behavioural BMLD occur up to the cortical level, as reflected by the 7(or13)-Hz ASSRs. Further,
these processes occur either in a different pathway (or different neuronal groups) or above the brainstem auditory processing reflected by the 80-Hz ASSRs. Although results of the current study suggest that the BMLD is generated at the cortical level but not at the brainstem or the thalamus level, the brainstem and thalamus are considered essential in maintaining and transmitting phase synchrony to higher levels of the auditory system (Fowler & Mikami, 1995). It is also possible that the BMLD is generated at the brainstem level but is only manifested in the EPs generated above the brainstem.

The results of the present study also suggest that the cortical ASSRs are not directly related to the slow cortical transient N1-P2 responses, and that their generators may be different from each other. The ASSR BMLDs may also reflect processes that are, at least partially, different from those underlying the behavioural BMLD, and thus may reflect a different type of processing compared to that represented by the transient evoked potentials. In contrast with the cortical transient N1-P2, the cortical ASSRs may reflect the output of neural populations which previous research has shown to be insensitive to interaural phase differences in noise but sensitive to signal interaural phase differences (Palmer, Jiang, & McAlpine, 1999).

Finally, further studies using middle latency ASSR to derive the BMLD, investigation of the ASSR amplitude and phase changes in the various BMLD conditions, and expanding the subject sample size may provide additional insights and information to the auditory mechanisms underlying binaural processing and psychoacoustic phenomenon such as the BMLD.
REFERENCES


APPENDIX A:

INDIVIDUAL BEHAVIOURAL THRESHOLDS AND BMLDs
## Individual Behavioural Thresholds and BMLDs

### 7(or13)-Hz AM Tone

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**Mean** 9.3 8.7

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**Mean** 8.5 10.5
APPENDIX B:

INDIVIDUAL ASSR THRESHOLDS AND BMLDs
## Individual ASSR Thresholds and BMLDs

### 7(or 13)-Hz AM Tone

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Mean: 5.8 dB, 1.5 dB

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Mean: 0.9 dB, 0.9 dB
APPENDIX C:

PILOT STUDIES
PILOT STUDY ONE

Number of EEG Sweeps Required to Record a 7-Hz ASSR

Before conducting the present experiment, a pilot study was carried out to determine the average number of EEG sweeps required to record a “present” 7-Hz ASSR in the conditions $S_o$, $S_oN_o$, and $S_xN_o$. Four normal-hearing subjects participated in this pilot study. Their behavioural BMLD was obtained first and the masker level required to just mask the signal in the $S_oN_o$ condition behaviourally was used in both $S_oN_o$ and $S_xN_o$ conditions for the ASSR recording. Eight consecutive trials, each consisting of 12 sweeps, were recorded for each of the three conditions. Therefore, a total of 96 sweeps were averaged for each condition. It was found that, at a signal level of 60 dB SPL, a present 7-Hz ASSR response was usually obtained after averaging 24 to 48 EEG sweeps for the $S_o$ condition. No 7-Hz ASSR, however, was recorded for the $S_oN_o$ and $S_xN_o$ conditions at their behavioural masking thresholds. There was a need, therefore, to carry out a second pilot study to determine the difference between the behavioural and ASSR masked thresholds in both the diotic and dichotic conditions.

PILOT STUDY TWO

Difference between the Behavioural and 7-Hz ASSR Thresholds in Conditions $S_oN_o$ and $S_xN_o$

Two normal-hearing subjects participated in this second pilot study. For both $S_oN_o$ and $S_xN_o$ conditions, the 7-Hz ASSR masked thresholds were obtained with about 20-26 dB less masking than the behavioural counterparts. Therefore, in order to obtain a present 7-Hz ASSR in the diotic and dichotic conditions, the masker level has to be further attenuated by about 20-26 dB from the behavioural thresholds. For both subjects, the behavioural BMLD obtained closely approximated their 7-Hz ASSR BMLD.
PILOT STUDY THREE

Difference between the Behavioural and 80-Hz ASSR Thresholds in Conditions S\textsubscript{0}N\textsubscript{0} and S\textsubscript{p}N\textsubscript{0}

Two normal-hearing subjects participated in this third pilot study. It was found that the behavioural threshold for the S\textsubscript{0}N\textsubscript{0} condition was close to the 80-Hz ASSR threshold for both S\textsubscript{0}N\textsubscript{0} and S\textsubscript{p}N\textsubscript{0} conditions. That is, no 80-Hz ASSR BMLD was found, although a behavioural BMLD was present for both subjects.