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Release from masking: Behavioral and physiological masking level differences

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Release from Masking: Behavioral and Physiological Masking Level Differences

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Dedication

This document is dedicated to my husband, Drew Hodgson and my parents Mark and Beverly McClements for all of your immeasurable support, love, and guidance during both my graduate school career and the culmination of this dissertation. Drew, your love and support have been without parallel and I know it is that which has helped me persevere through the ups and downs of these past three years. Thank you especially to my parents for instilling in me a love for learning and desire to excel both in academics and in life. You have taught me so much, Mom and Dad, and I feel so blessed to have parents like you. Also to my sisters, grandparents, extended family and friends who have supported and encouraged me throughout these past three years – I am truly grateful.
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Abstract

Binaural hearing offers several advantages over monaural hearing and is believed to be one factor that is involved in the ability to understand speech in background noise. Binaural hearing involves analysis of interaural timing and intensity differences in signals arriving at the two ears which provides listeners with sound localization cues as well as signal in noise detection. When sounds arrive at each ear at slightly different times, there may be a release from the effects of background noise, allowing listeners to detect softer sounds in noise. Masking Level Differences (MLDs) have been widely used to evaluate behavioral binaural processing. However, the literature inconsistently reports a release from masking in physiological responses. The purposes of this study were 1) to establish the feasibility of measuring physiological masking level differences using the frequency-following response (FFR), and 2) to characterize the relationship between behavioral and physiological measures of masking level differences (MLDs). Fourteen young adults (ages 21-26) with clinically normal hearing sensitivity participated in this study. Stimuli for behavioral and physiological conditions were 500 Hz tonebursts presented in one-third octave narrowband noise. Three phase conditions were tested: $S_oN_o$, $S_oN_\pi$, and $S_\pi N_o$. Behavioral MLDs were assessed using an adaptive 2AFC procedure. Physiological MLDs were assessed using the frequency-following response, an auditory evoked potential reliant on phase-locked neural activity. FFR analysis focused on amplitude measures. Speech-in-noise understanding was also tested using the Words-in-Noise test (WIN). Behavioral MLDs were 8.29 dB (std. dev = 4.09) for $S_o N_\pi$ and 10.03 dB (std. dev = 4.96) for the $S_\pi N_o$ condition. Physiological MLDs did not indicate a robust release from masking, especially for the $S_\pi N_o$ condition. Correlations between behavioral and
physiological MLDs were not significant. However, FFR amplitude differences between having the signal, or 500 Hz tone, in phase between the ears (e.g., $S_0N_0$) and $180^\circ$ out of phase (i.e., $S_\pi N_0$) predicted behavioral $S_\pi N_0$ MLDs. These findings may help to clarify which scalp-recorded auditory evoked potentials reflect binaural processing in humans and report the first brainstem auditory evoked potentials in humans that can predict behavioral masking level differences.
Chapter I

Introduction

The purposes of the present study were 1) to establish the feasibility of measuring physiological masking level differences using the frequency-following response (FFR), and 2) to characterize the relationship between behavioral and physiological measures of masking level differences (MLDs) in an effort to examine a possible brain-behavior relationship. This was measured using one behavioral test, Masking Level Difference (MLD), one physiologic measure, the Frequency Following Response (FFR), and one measure of speech understanding in noise, the Words-in-Noise (WIN) test. It was hypothesized that physiological MLDs would be present for both the $S_πN_o$ condition and the $S_oN_π$ condition (showing the same trend as behavior) and that there would be a strong correlation between the behavioral MLD and FFR-MLD. It was also hypothesized that participants with the largest behavioral MLDs would be the same individuals with the largest physiological MLDs and that those individuals with the smallest behavioral MLDs would be the same individuals with the smallest physiological MLDs. Additionally, it was hypothesized that those individuals with the most robust release from masking on both the behavioral tone-in-noise detection task and the FFR would be the same individuals with the best performance (e.g., most release from masking in the spatially-separated versus co-located condition) on the WIN test.
Chapter II: Review of Literature

Introduction

A nearly universal listening complaint of listeners, particularly older individuals, is some degree of difficulty understanding speech in the presence of noise (Pichora-Fuller & Schneider, 1991). This is problematic because noise, whether it be competing speech, music, cafeteria noise, traffic noise, etc., is encountered frequently in everyday listening situations. It has been suggested by numerous researchers that age-related declines in binaural processing may in part contribute to these speech-in-noise difficulties (e.g., Koehnke & Besing, 2001). Additional factors of reverberation and reduced auditory sensitivity further confound the ability to understand speech in the presence of background noise (Koehnke & Besing, 2001). Speech is a complex, dynamic signal that is made up of three main temporal features: envelope, periodicity, and fine-structure information (e.g., Rosen, 1992). These three temporal characteristics of speech broadly encompass a variety of acoustic cues including prosody, intonation, intensity, duration, and segmental features. The ability to understand speech involves the ability to perceive and identify individual phonemes as well as to synthesize and interpret the incoming speech signal so that it accurately represents the message being conveyed (Pichora-Fuller, Schneider, & Daneman, 1995). Certainly, age-related declines in auditory processing are not the only factors that contribute to speech-in-noise difficulties experienced by elderly listeners. Age-related cognitive declines such as those that effect selective attention, higher-level speech comprehension, working memory, and speed of processing likely negatively impact speech understanding as well (for review, see Pichora-Fuller & Singh, 2006).
Binaural Hearing and Speech-in-Noise Understanding

As stated above, one of the factors believed to be involved in the ability to understand speech in the presence of competing noise is binaural hearing, or hearing with two ears. Numerous advantages of binaural hearing have been reported in the literature including, but not limited to, signal detection-in-noise, speech-in-noise, and localization. Binaural hearing broadly describes our ability to use and capitalize on interaural comparison cues arriving at the two ears (Akeroyd, 2006). The human auditory system is sensitive to two types of interaural comparison cues, the main ones being interaural intensity differences (IIDs) or interaural level differences (ILDs) and interaural timing differences (ITDs) (Akeroyd, 2006). Interaural intensity differences, influenced by the head-shadow effect, help with localization of high-frequency sounds and refer to intensity differences between the two ears of an incoming signal (Akeroyd, 2006). Interaural timing differences, which help to determine the direction of low-frequency sounds, refer to the timing difference of the signal arriving at the two ears (Akeroyd, 2006).

These interaural comparison cues allow the signal of interest and the noise to be processed separately that creates an enhanced signal-to-noise ratio, particularly when a sound source originates from a listener’s side. A person’s ability to use these binaural processing cues to attend to and understand a single speaker in the presence of competing noise has historically been called the “cocktail party effect” (Koehnke & Besing, 2001). This term, first introduced by Cherry (1953), refers to the ability to selectively attend to, discriminate, and understand the target signal of interest in the presence of competing noise, and likely reflects the advantage of two ears instead of one.
Masking Level Difference – A Historical Perspective

Webster (1951) was the first to introduce the term “masking level difference” (MLD). Other names for this phenomena include “binaural release from masking,” “binaural unmasking,” or “binaural masking level differences (BMLDs).” Masking Level Differences have been widely used as a measure of behavioral binaural processing in both clinical populations, as well as those with normal hearing. Masking level differences have historically been used to describe the auditory system’s ability to detect interaural timing differences (McFadden & Pasanen, 1978). The theoretical concept behind masking level differences as first described by Hirsh (1948) and Licklider (1948) classically refers to the comparison between a homophasic, or baseline, condition and an antiphasic condition when either the signal (S) or the masker (N) is interaurally phase-shifted (e.g., 180°) relative to the baseline condition (Licklider, 1948). It is well known that in the presence of competing noise, the ability to detect and localize a signal of interest is largely dependent on the interaural phase relationships between the signal and the noise (Webster, 1951). Hirsh (1948) and Licklider (1948) both demonstrated in separate experiments that the audibility (intelligibility) of a binaural signal (either speech or pure tones) is improved during antiphasic conditions (where either the signal or the noise is out of phase) compared to the homophasic condition (in which signal and noise were either in or out of phase).
Masking Level Difference Test Paradigm

The traditional MLD test paradigm includes behavioral detection of tones-in-noise using two masking conditions: homophasic and antiphasic (Webster, 1951). The comparison of these two conditions is used to derive the Masking Level Difference, or the amount of unmasking present. Homophasic (or baseline) refers to signals that are identical in both ears, meaning there no interaural comparison cues available to “unmask” the signal (Pichora-Fuller & Schneider, 1991, p.1411). The most commonly reported homophasic condition is \( S_oN_o \), where the signal and the noise presented at each ear are in phase with the signal and noise presented to the other ear (Webster, 1951). Licklider (1948) and Hirsh (1948) both reported that for homophasic conditions, signal detection is poorer and there is no apparent advantage for binaural versus monaural hearing.

Antiphasic refers to signals that are presented at different phases to the two ears, which provides interaural comparison cues with which to unmask the signal, resulting in a lower (better) detection threshold compared to a homophasic condition (Pichora-Fuller & Schneider, 1991). While there are numerous ways the signal (S) and noise (N) can be manipulated to produce an antiphasic condition, the most commonly reported manipulation is an interaural phase difference of \( \pi \) radians (or a 180° phase shift) for either the signal or the noise separately (e.g., \( S_\pi N_o \) or \( S_oN_\pi \) representing a shift in either the signal or the noise respectively) (Wilson, Moncrieff, Townsend, & Pillion, 2003). \( S_\pi N_o \), the most commonly reported antiphasic condition in the literature and the one that often results in the largest MLDs, refers to a signal that is 180° out of phase between the two ears while the noise is presented in phase to both ears. \( S_oN_\pi \) is a masking condition in which the signal is presented in phase to both ears while the noise is interaurally phase-
shifted by 180°. Based on a study on cats with unilateral lesions at various nuclei along the auditory brainstem pathway, it is likely that the perceptual release from masking as seen in the MLD is the result of binaural processing in the brainstem at the level of the medial-superior olivary complex (MSO) (Jenkins & Masterton, 1982; for review of the anatomy and physiology of binaural hearing, see Moore, 1991).

The release from masking commonly seen under antiphase masking conditions reflects the auditory system’s ability to interpret and use interaural cues (including timing and intensity characteristics) when the signal and/or masker presented to one ear is out of phase with the same stimuli presented to the other ear. The masking level difference is calculated by subtracting the antiphase condition detection threshold (e.g., $S_aN_o$) from the $S_oN_o$ detection threshold (homophase condition) (Wilson et al., 2003). A larger MLD (in dB) is associated with a greater release from masking. MLDs are most robust at the low frequencies, about 15 dB below 1000 Hz, and decrease as a function of increasing frequency to about 3-4 dB for signals above 1500 Hz (Webster, 1951; Durlach, 1963; Green & Henning, 1969). Several studies have demonstrated that MLDs are larger when a narrowband masking noise is used when compared to those elicited in broadband masking noise (Bourbon & Jeffress, 1965; Hall & Harvey, 1984).

It has been suggested that low-level cells in the mammalian auditory brainstem, sensitive to interaural timing differences contribute at least in part to the mechanisms underlying the perceptual masking level difference (Palmer & Shackleton, 2002). The Coincidence-Detection Model, as first proposed by Jeffress (1948), describes a place theory of sound localization based on interaural timing differences and has been the predominant theory of sound localization in mammals since the 1940’s. Jeffress’ model
proposes a complex network of bi-polar neurons that are systematically arranged in delay lines, which allow the human auditory system to be sensitive to very small timing differences (e.g., coincidence detectors) in the arrival of a low-frequency signal at the two ears to assist in sound localization (Palmer & Shackleton, 2002).

**Characteristics that Affect the Size of the MLD**

MLDs can be recorded to various types of stimuli, including pure-tones and spondaic word stimuli. Likewise, there are a number of factors that can influence the size of the MLD effect including stimulus frequency, type of masking noise, masker level, and masking bandwidth. Webster (1951) reported that the size of the MLD is highly dependent on stimulus frequency. That is, with increasing frequency, the rate of MLD decline also increases (Webster, 1951). MLDs are the most robust for low frequencies and gradually reduce in magnitude with increasing stimulus frequency. That robust MLDs cannot be obtained at higher stimulus frequencies is thought to reflect the auditory system’s inability to use interaural timing cues above about 1000 to 1500 Hz (McFadden & Pasanen, 1974).

The type of masking noise used also has been shown to impact the robustness of the MLD. McFadden (1966) reported that the MLD obtained during burst masking noise were smaller than those obtained with continuous masking noise. Hirsh (1948) and other researchers (Hall & Harvey, 1984; Hall & Harvey, 1985) have demonstrated that the size of the MLD increases as a function of increasing masker level up to a certain level at which no further increases in the size of the MLD effect is seen. Pichora-Fuller and Schneider (1998) reported that for both young and older listeners in the presence of
broadband, burst masking noise, there were no systematic increases in the robustness of the MLD once the spectrum level of the masker level exceeded 27 dB SPL. That is, a plateau was reached by both groups at which an increase in the masking noise no longer resulted in an increase in the size of the MLD (Pichora-Fuller & Schneider, 1998).

**Masking Level Differences and Clinical Populations**

Reduced (poorer) MLDs have been reported to occur in various clinical populations. However, in regard to the effects of age on the MLD effect, there has not been a consensus in the literature. Pichora-Fuller and Schneider (1991) measured antiphasic thresholds for young and older listeners using burst and continuous broadband masking noise. They found a significant difference between the MLDs of young and older listeners, even when the effect of minimal hearing loss was systematically accounted for. Overall, higher detection thresholds were noted in the older listeners for $S_{p}N_{o}$, but no significant differences were noted for the homophasic condition ($S_{o}N_{o}$) (Pichora-Fuller & Schneider, 1991). Likewise, Grose, Poth, and Peters (1994) measured MLDs to 500 Hz tones and spondees in young normal hearing listeners and older listeners with normal hearing out to at least 2000 Hz. Similar to the findings of Pichora-Fuller and Schneider (1991), Grose et al., (1994) reported that the older listeners demonstrated smaller MLDs for both tones and spondees compared to the young normal hearing listeners. Grose et al., (1994) reported that this difference was due in most part to the higher detection threshold for the $S_{p}N_{o}$ condition. The results of these two studies suggest that older listeners are less able to capitalize on interaural comparison cues to unmask a signal in noise, independent of peripheral hearing loss.
Jerger, Brown, and Smith (1984) studied the effects of symmetrical and asymmetrical peripheral hearing loss on the MLD at 500 Hz in a large retrospective study. While the authors report that the “boundary frequency” (the frequency at which the high-frequency hearing loss begins) does affect the size of the MLD, overall for individuals with normal hearing at 500 Hz but elevated thresholds at higher frequencies in one or both ears, the effect of sensorineural hearing loss is minimal on the 500 Hz MLD (Jerger et al., 1984). However, they report that the effect of hearing loss at the stimulus frequency, particularly asymmetrical sensorineural hearing loss, can have a significant effect on the size of the 500 Hz MLD.

Olsen, Noffsinger, and Carhart (1976) measured MLDs at 500 Hz and spondees in eight different groups, including normal-hearing individuals, conductive hearing loss, cochlear hearing loss (including noise-induced hearing loss and presbycusis), eighth nerve tumors, Meniere’s disease, and Multiple Sclerosis (MS). They defined an MLD of less than 7 dB as an abnormally small release from masking for $S_\pi N_\sigma$ and 4 dB for $S_\sigma N_\pi$ respectively (Olsen et al., 1976). For the 500 Hz MLDs, they observed that those with cortical lesions and noise-induced hearing loss performed similarly to the normal hearing control group. However, an abnormally small MLD was often observed in subjects with eighth-nerve lesions, Meniere’s disease, and MS (Olsen, et al., 1976).

Novak and Anderson (1982) conducted a study that compared the MLD in quiet and in noise in young normal-hearing controls to older adults with normal hearing and also attempted to differentiate the types of presbycusis using the masking level difference. They found no significant difference in the size of the MLD between the young normal and old normal subjects in either quiet or noise. However, they reported
that the group of individuals with suspected neural presbycusis had on average MLDs in quiet that were significantly larger than the other groups and significantly reduced MLDs in noise (Novak & Anderson, 1982). They suggest that increased levels of internal noise in the system as suspected in those with neural presbycusis may have contributed to this finding.

More recent studies have also shown reduced MLDs in clinical populations. One of the purposes of a study conducted by Porter, Grantham, Ashmead, and Tharpe (2014) was to compare the binaural release from masking in children with Down syndrome to their typically-developing peers. They found that children with Down syndrome displayed a smaller binaural release from masking (e.g., reduced MLDs) compared to their typically-developing counterparts similarly matched for age and hearing sensitivity. However, interestingly, when the MLDs of adults with Down syndrome were compared to the control adults, no significant differences were found, suggesting a possible maturation effect in the ability to use interaural comparison cues for children with Down syndrome (Porter et al., 2014).

Similarly, Lu, Litovsky, and Zeng (2010) conducted a study that examined MLDs in actual and simulated bilateral cochlear implant (CI) users, as well as how factors including electrode location in the cochlea, stimulus signal frequency, and auditory deprivation affect binaural unmasking in bilateral CI users. The study’s main purpose was to measure MLDs at two phase conditions (S₀N₀ and S₂N₀) across several pairs of pitched-matched and loudness-balanced electrodes at three different frequencies (125, 250, and 500 Hz) in order to better understand why MLDs are reduced in bilateral CI users compared to normal-hearing listeners. They observed binaural unmasking (average
MLD of 4.6 ± 4.9 dB) in the CI users across various electrode locations under different signal/masker conditions. However, a high degree of inter-subject variability was observed in regard to the robustness of the MLD. The authors also reported a significant effect for phase condition and electrode pair for the 125 Hz stimuli only, suggesting that MLDs are more likely to be present at lower signal frequencies (Litovsky et al., 2010). Finally, the normal-hearing controls using the acoustic CI stimulation performed better than their CI counterparts, seen most evidently for the $S_\pi N_0$ condition. The authors postulate that poorer performance as seen in the bilateral CI users compared to normal-hearing controls particularly for the $S_\pi N_0$ condition suggests deficits in the central processing of binaural information.

Wilmington, Gray, and Jahrsdorfer (1994) measured various tasks of binaural processing, including masking level differences, in patients pre and post-operation to correct unilateral congenital conductive hearing losses in an effort to examine the effect of abnormal early experience. The authors report a significant improvement in the size of the MLD pre to post-surgery in these subjects. However, these subjects still performed poorer on average than their normal-control counterparts. Significant improvement on all tasks of binaural processing post-operation was reported. However, the degree of improvement varied across tasks suggesting that abnormal early experience can have a differential effect on various measures of binaural hearing, particularly on more complex tasks of binaural processing (Wilmington et al., 1994).
**Frequency-Following Response (FFR)**

One way the brain represents frequency is through phase-locking. When populations of neurons phase lock together, they can produce a group response that closely mimics, or follows, the periodicity of the stimulus. (Worden & Marsh, 1968). The Frequency-Following Response (FFR), as first described by Worden & Marsh (1968), describes a microphonic-like, or neurophonic, neural response that is synchronized to auditory stimuli with an upper frequency limit of approximately 2000 Hz (for a review, see Krishnan, 2007). The human FFR is a scalp-recorded auditory evoked potential that reflects sustained phase-locked neural activity from the auditory brainstem that closely mimics the acoustic characteristics of the stimulus. The FFR encodes both fine structure (harmonics) and temporal envelope (fundamental frequency) information of the stimulus. Unlike the traditional click-evoked ABR, which is a more global measure of time-locked neural activity to the onset of a stimulus (Jewett, 1970) the FFR is able to reflect how the periodicity of a stimulus is neurally encoded because it relies on sustained phase-locked neural activity (Worden & Marsh, 1968). The FFR can be elicited by numerous types of stimuli, some examples being puretones, synthetic speech sounds (including steady-state vowels and consonant-vowel stimuli), naturally-produced vowels, and tonal sweeps (for a review, see Krishnan, 2007). While the upper limit of phase-locking in the human auditory brainstem is not firmly established, FFRs can be reliably recorded to puretones of frequencies up to approximately 1500 Hz in humans (Krishnan, 2007).

The neural generators of the FFR consist of multiple nuclei in the auditory brainstem, including the Cochlear Nucleus, Superior Olivary complex (SOC), Lateral
Lemniscus, and Inferior Colliculus. It is believed that the Inferior Colliculus is the primary neural generator for the FFR when recorded from the scalp with electrodes arranged in a vertical montage, such as Cz (vertex) to earlobe (Smith, Marsh, & Brown, 1975). As a result, FFRs have traditionally been recorded from a vertical montage. However, recording FFRs from a horizontal montage (e.g., earlobe to earlobe or mastoid-to-mastoid) is believed to reflect neural activity from lower, more caudal brainstem generators, like the auditory nerve (e.g., Bidelman, 2015). Recording from these two electrode montages may represent different neural generators in the auditory brainstem and responses recorded from these different montages have been reported to have slightly different characteristics (Bidelman, 2015; Galbraith, 1994).

**Comparison of Behavioral and Physiological MLDs**

*Overview of Literature*

A limited number of studies have compared binaural processing performance on a behavioral masking level difference task to an electrophysiological measure using the same stimuli. However, some studies have been conducted that have addressed this issue using cortical potentials including the late P2 auditory evoked potential (e.g., Fowler and Mikami (1992) and the auditory brainstem response (ABR) (Jerger, Hannley, & Rivera, 1982). Fowler and Mikami (1992) report that the response characteristics of the late auditory evoked potentials are similar to but not identical to those observed for the behavioral MLD. While Jerger et al., (1982) report observing a trend in which smaller MLDs were associated with subjects who had a delay in latency or absence of wave III. Although there have been several studies that have evaluated binaural processing using
the FFR, those studies have focused only on physiological measures and how they are affected by interaural intensity or time differences (e.g., Ballachanda & Moushegian, 2000) or the binaural interaction component (e.g., Krishnan & McDaniel, 1998). Of the FFR studies that have been conducted, there are inconsistent reports of release from masking in physiological responses generated in the auditory brainstem (Wilson & Krishnan, 2005; Wong & Stapells, 2004). Thus, the relationship between perceptual and physiological measures of unmasking remains unclear. Since it has been demonstrated that the MLD is most robust at lower frequencies and decreases in magnitude as a function of increasing frequency (e.g., Green & Henning, 1969), a comparison between the FFR, which is dependent on neural phase locking and is also more robust at low frequencies, and the behavioral MLD seems logical to see if similar trends emerge between the two measures. The approaches and findings of Wilson and Krishnan (2005) and Wong and Stapells (2004) will be described below.

Wilson and Krishnan (2005) authored, to our knowledge, the only peer-reviewed manuscript describing an investigation into behavioral and physiological processing related to MLD, using the FFR. One of the purposes of the Wilson and Krishnan study was to establish if physiological unmasking was present in FFR recordings and what relationship existed between perceptual MLDs and FFR unmasking. Wilson and Krishnan (2005) compared behavioral MLDs to FFR recordings in MLD stimulus conditions (S_oN_o, S_πN_o, and S_oN_π) in young, normal-hearing listeners. Results of the study showed larger FFR signal-to-noise ratios in antiphasic conditions relative to FFR signal-to-noise ratios in homophasic conditions, consistent with unmasking.
The FFR MLDs reported by Wilson and Krishnan were elicited by conventional behavioral MLD homophasic ($S_oN_o$) and antiphasic ($S_\pi N_o$ and $S_oN_\pi$) test conditions. The amount of FFR unmasking was derived by subtracting the FFR SNR of an antiphasic condition ($S_\pi N_o$ or $S_oN_\pi$) from the FFR SNR of the homophasic condition (e.g., response SNR of $S_oN_o$ – response SNR of $S_\pi N_o$ = degree of FFR unmasking). The most robust FFR-MLD amplitudes were found for the $S_oN_\pi$ condition (mean = 5.00 dB). This physiological finding is opposite of behavioral MLD literature in which the largest behavioral MLDs are reported for the $S_\pi N_o$ condition. The authors also found that individuals with the most robust FFRs to tones-in-quiet, without masking noise (i.e., $S_o$, and $S_\pi$) had the smallest FFR MLDs. They also reported no clear trend or relationship between the size of the psychoacoustic MLD and the FFR-MLD amplitude, although the brain-behavior relationship was not evaluated statistically. That is, individuals with larger behavioral MLDs did not necessarily have the largest FFR MLDs in either antiphasic condition.

Several methodological factors in Wilson and Krishnan (2005) may have contributed to this unexpected relationship between perceptual MLDs and physiological FFR-MLDs. First, this study used an average of four ascending trials to find masked thresholds for the psychoacoustic data, as opposed to the typical multi-interval forced choice procedure. Second, there was a mismatch between behavioral and physiological conditions; acoustic signal-to-noise ratios of stimuli did not always match between the behavioral and physiological MLD conditions. The authors reported that if the criterion reduction in FFR SNR was not decreased by 50%, the masker intensity was increased 3-6 dB until a sufficient FFR SNR reduction was recorded (at least 50%). Third, a low
stimulus level of 56 dB SPL was used, which is close to the stimulus level of FFR thresholds; this may have resulted in small amplitude responses that were close to the noise floor.

The second study to evaluate physiological MLDs using a steady-state response was Wong and Stapells (2004). The purpose of this study was to examine the brainstem and cortical mechanisms that may contribute to the MLD in normal-hearing human adults. The study recorded behavioral and physiological MLDs using stimuli that were 500 Hz amplitude-modulated tones. Amplitude-modulation following responses, or auditory steady-state responses (ASSRs), were elicited with three modulation frequencies: 80 Hz (primarily brainstem) and 7 or 13 Hz (primarily cortical). The study found that ASSR MLDs were significantly smaller than those elicited by the behavioral MLDs. Stated another way, the behavioral MLD elicited for the two antiphasic conditions ($S_\pi N_o$ and $S_o N_\pi$) were significantly larger than those elicited by the ASSR MLD for the same conditions. Wong and Stapells (2004) also report that only the cortical ASSRs elicited either at 7 or 13 Hz produced a physiological MLD, and this effect was only seen for the $S_\pi N_o$ condition. A MLD was not obtained for the cortical ASSRs when the noise was interaurally phase-shifted (e.g., $S_o N_\pi$). Likewise, no MLD was produced for the brainstem ASSRs (80 Hz) for either the $S_\pi N_o$ or $S_o N_\pi$ condition. The authors offer several hypotheses as to why a cortical ASSR MLD was present, while no measurable MLD was elicited from the brainstem ASSR. They suggest that the behavioral MLD may be the result of auditory processing up to and including the cortex. They also suggest that the brain processes responsible for the behavioral MLD may occur in a different neuronal pathway or at a nuclei beyond that which would be reflected by the 80 Hz ASSR. Finally,
the authors propose that the MLD may be generated in the auditory brainstem but is only reflected on those auditory evoked potentials which measure beyond the brainstem.

Summary

In summary, it has been shown that binaural hearing plays an integral role in the ability to detect speech-in-noise, signals-in-noise, and localization and is particularly important for comparison of interaural timing differences. The MLD has been widely-used as a measure of behavioral binaural processing. While numerous studies have confirmed a robust behavioral release from masking in young, normal-hearing listeners and reduced (poorer) MLDs in elderly listeners and clinical populations, few have compared behavioral measures of masking level differences to physiological measures of the same kind. The question of the relationship between perceptual and physiological unmasking at the level of the auditory brainstem in normal-hearing individuals remains. This relationship, once studied, may also have important implications clinical populations, including for those with hearing loss and/or older listeners. The application of FFR MLDs in older listeners or other clinical populations may be applied to better understand effects of altered temporal processing. However, in order to establish the feasibility of measuring this type of response in older listeners, it has to be measured first in young, normal-hearing individuals.

This dissertation project was intended to establish the feasibility of measuring physiological masking level differences using the FFR and to characterize behavioral and physiological measures of masking level differences in an effort to examine a possible brain-behavioral relationship. The purposes of this project were to:
(1) To establish the feasibility of measuring physiological masking level differences using the frequency-following response (FFR), an auditory evoked potential dependent on phase-locked neural activity. This response was measured across various signal-to-noise ratios and three phase conditions: $S_{o}N_o$, $S_{\pi}N_o$, and $S_{o}N_{\pi}$.

(2) To characterize the relationship between behavioral and physiological measures of masking level differences (MLDs).

**Hypotheses:**

1. We hypothesized that physiological MLDs would be present for both the $S_{\pi}N_o$ condition and the $S_{o}N_{\pi}$ condition.

2. There will be a strong correlation between the behavioral MLD and FFR MLD. Those individuals with larger (better) behavioral MLDs are expected to have larger (better) FFR MLDs, and those individuals with smaller (poorer) behavioral MLDs are expected to have smaller (poorer) FFR MLDs.
Chapter III

Methods and Materials

Subjects

Fourteen young, normal-hearing subjects (ages 21 to 26, mean age = 22.57, standard deviation = 1.34) two males, twelve females) participated in this study.

Inclusion criteria included audiometric thresholds ≤ 25 dB HL at octave frequencies 0.25-8 kHz with interaural asymmetries ≤10dB at each frequency. All subjects included in the study were monolingual native English speakers with normal tympanometric measures, no known history of otological or neurological disease, with less than seven years of formal musical training, and not currently taking centrally-acting prescription medications. (One subject included in this present data set did have more than seven years of formal musical training). Subjects were recruited primarily through word-of-mouth and fliers posted on the James Madison University campus. Subjects were compensated $10 per hour for each hour of his/her participation. All methods and procedures used in this study were approved and in accordance with the International Review Board (IRB) at James Madison University.

Seven additional subjects were excluded from the study and had only partial data collected. Four of these subjects were excluded due to inconsistent detection thresholds and poor, unreliable tracking functions on the behavioral tone-in-noise detection task. Two subjects were excluded due to interaural asymmetries of greater than 10 dB at one or more of the audiometric test frequencies. The last subject was excluded due to incomplete behavioral data for one of the antiphasic conditions (SNπ) and an artifact rejection of greater than 50% during several of the FFR recordings.
Procedure

Data collection consisted of several different types of measures. Behavioral tone-in-noise detection was used to calculate behavioral masking level differences. Physiological tone-in-noise detection was used to calculate physiological masking level differences. Speech-in-noise understanding was tested using the Words-in-Noise test (WIN). The order of phase conditions across behavioral and physiology was randomized across subjects. However, the behavioral tone-in-noise detection task was always completed prior to recording the FFR. Data collection typically consisted of two test sessions of approximately four hours each.

Stimuli Common to Behavioral and Physiological MLD Conditions

Stimuli for both the behavioral MLD and physiological FFR conditions were 500 Hz tonebursts presented in one-third octave noise centered on 500 Hz. Stimulus duration was 250 ms, including a 15 ms rise/fall time with a Hanning window. Stimuli were generated with a sampling frequency of 44.1 kHz. For behavioral tone-in-noise detection conditions, the tone level was fixed at 70 dB SPL, while the noise level varied to adjust signal-to-noise ratio. Calibration of signal-to-noise ratios was performed using the spectrum level of the noise (Figure 1), rather than RMS dB SPL. Onset polarity was positive. Magnetically shielded ER-3A insert earphones with double-length tubing delivered stimuli to both ears for the physiological and behavioral conditions.
Figure 1. Fast Fourier Transform of an example stimulus with 10 dB SNR. Tone level was fixed at 70 dB SPL; spectrum level of the 1/3rd octave band noise changed to adjust signal-to-noise ratio.

Behavioral Procedure - Masking Level Difference

Methods for the behavioral MLDs followed those of Pichora-Fuller and Schneider (1991). Tone-in-noise detection was tested in three conditions: SoNo, SπN₀, and S₀Nπ. Detection thresholds (in dB signal-to-noise ratio) from these tone-in-noise detection tasks were used to calculate MLDs. An adaptive two-interval, two-alternative forced choice procedure (2AFC), with a two-down, one-up adaptive rule (Levitt, 1971) was used to test tone-in-noise detection. Signal-to-noise ratio varied along the adaptive track. An initial 4 dB step size changed to a 2 dB step size after the fourth reversal. Each run was terminated after the twelfth reversal. This adaptive procedure targeted the 70.7% correct point of the psychometric function. A custom Matlab program (version R2013B) was developed for this procedure. The subject was instructed to identify in which of two intervals he/she heard the "tone" in noise by using a computer mouse to click on the interval they thought contained the tone as displayed on a computer monitor in the testing booth. The subject was given immediate feedback on the correctness of his/her response.
A minimum of three runs for each of the phase conditions was collected to ensure consistency between runs, with each run taking approximately five minutes to complete. Each subject was given at least one practice run to orient them to the task; experimental trials began when participants demonstrated consistent tracking functions.

At the conclusion of the behavioral task, a reconstructed psychometric function was created in Matlab from the average of each of the runs for each phase condition. An example of this procedure is illustrated in Figure 2. The reconstructed psychometric function was constructed by taking the proportion correct $[P(C)]$ at each signal-to-noise ratio tested for each phase condition. Any run that showed a poor tracking function (i.e., indicated attention lapses) was excluded from the final average. These reconstructed psychometric functions were used to guide which signal-to-noise ratios to test for the FFR conditions.

![Figure 2](image_url)

**Figure 2.** Illustration of reconstructed psychometric functions from adaptive tracks. Each panel corresponds to a different phase condition. Average reconstructed psychometric functions are shown with their logistic fits.
Physiological Procedure - Frequency-Following Response

FFR Recordings

A Neuroscan SynampsRT acquisition system was used to record FFRs from a three-channel recording (Krishnan, Xu, Gandour, & Cariani, 2005; Swaminathan, Krishnan, Gandour, & Xu, 2008). The non-inverting electrode was Cz (vertex) and the three inverting channels had electrodes at the nape-of-the-neck, left earlobe, and right earlobe. The ground electrode was located at the high forehead (Fz). Absolute electrode impedances were below 5 kΩ and inter-electrode impedances were kept within 1 kΩ. Stimulus onset asynchrony was 533.33 ms. The online electroencephalography (EEG) activity was band-passed filtered from 30 Hz to 3000 Hz, the analysis time window was 0-270 ms, and the analog-to-digital sampling rate was 20 kHz. A minimum of 1000 individual, artifact-free sweeps were collected for each condition. Online artifact rejection was completed so that any sweep with a voltage exceeding ±30 µV was rejected. Testing was conducted in a double-walled, sound-attenuated booth with the subject seated in a reclining chair and instructed to relax quietly. There was a five minute silent period between each FFR condition. Each recording took approximately ten minutes to complete.

Physiological tone-in-noise detection thresholds were measured using the same tone-in-noise stimuli that were used in the behavioral task. A bracketing procedure was used to determine physiological tone-in-noise detection thresholds. For each phase condition (e.g., S_oN_o), the initial SNR presented was at the plateau of the average reconstructed psychometric function (e.g., 20 dB SNR) and descended in 8 dB steps until the response was absent; signal-to-noise ratio then increased in 4 dB steps until the
response was present, then descended in 2 dB steps to define threshold for physiological tone-in-noise detection if time allowed.

Data analysis was based on amplitude measurements and phase coherence (PC) (Batra, Kuwada, & Maher, 1986; Dobie & Wilson, 1989; John, Lins, Boucher, & Picton, 1998). In this document, physiological analyses will focus on amplitude. Detection threshold for amplitude was defined as the lowest (poorest) signal-to-noise ratio at which a present response was obtained. Response absence or presence was determined using an objective detection algorithm (F-test) (John et al., 1998). Response amplitude signifies the averaged magnitude of the neural response. Custom MATLAB programs were created for FFR amplitude-analysis. Fast Fourier Transforms (FFTs) of individual FFR waveforms were performed prior to the amplitude analysis. To achieve an FFT resolution of 0.96 Hz, consecutive pairs of sweeps were concatenated (John et al., 1998); because stimulus frequency was specified using coherent sampling the FFR was limited to one bin, or point, in the FFT output. FFR amplitude was obtained from the FFT bin where the averaged response was located (i.e., the 500 - 501 Hz bin). The mean of five FFT bins above and below (+10 Hz) the response bin was used as a noise estimate. The resulting signal-to-noise ratio from the amplitude and noise measures was used as an F-ratio with 2, 20 degrees of freedom (Dobie & Wilson, 1996). A p-value of <0.05 was used as the criteria to determine if the FFR amplitude was significantly greater than the surrounding background noise and would indicate response presence or absence. Figure 3 illustrates individual FFR data across a range of SNRs.
Figure 3. Individual data from a 22 year old subject. **Top Row** An FFR waveform that was elicited using an $S_o N_o$ 500 Hz toneburst with a 20 dB SNR. **Bottom Row** Examples of response FFTs at various signal-to-noise ratios tested for the $S_o N_o$ condition. The FFR amplitude (shown at red FFT bin) decreased as the acoustic SNR of the stimulus decreased; response was absent at -12 dB SNR.

Normalized FFR amplitude was also used to compare trends in behavioral P(C) and FFR amplitude across signal-to-noise ratio. Each individual’s maximum FFR amplitude for a given phase condition (e.g., $S_o N_o$) served as their normalization reference for their data in that same phase condition. This approach resulted in behavioral P(C) and normalized FFR amplitude both having values scaled from 0 to 1.0. Figure 4 demonstrates how having both P(C) and normalized FFR amplitude scaled from 0 to 1 facilitates comparison between the two measures by plotting them on a double y-axis figure.
Figure 4. This double y-axis figure compares individual perception and physiology data from the same subject. *Left axis*: psychometric function reconstructed from several adaptive tracks. *Right axis*: normalized FFR amplitude across SNRs. These data are from the 500 Hz $S_oN_o$ condition. Logistic fits are shown for these individual P(C) and FFR data.

Speech Perception in Noise

The Words-in-Noise (WIN) test (Wilson & Burks, 2005) was administered in two test conditions: spatially separated and co-located. The WIN test assesses speech understanding in the presence of multi-talker babble at various signal-to-babble ratios (Wilson & Burks, 2005). Seven different signal-to-noise ratios ranging from 16 dB SNR to -8 dB SNR were presented in a descending order, using a 4 dB step size. The 50% correct point for each individual run was calculated by fitting a 3rd degree polynomial curve to the percent correct across SNR data (Wilson & Burks, 2005). This 50% point was obtained using the “polyval” function in Matlab R2013b. Figure 5 shows an example of individual WIN data from each of the conditions. The level of the speech (monosyllabic words) decreased, while the level of the multi-talker babble was fixed. In the spatially-separated condition, multi-talker babble originated from a speaker at 90°.
azimuth (to the right side) and speech at 0° azimuth. In the co-located condition, both the speech and noise originated from a speaker in front of the subject at 0° azimuth. A research version of the WIN materials was used that allowed speech and multi-talker babble to be routed separately.

**Figure 5.** Shows the 50% point for an individual subject (#149) for list 1 and list 2 for each test condition respectively. Within each panel is an estimate of the SNR corresponding to 50% correct. As expected, a lower (better) 50% correct point is achieved for the spatially-separated condition than the co-located condition. The far right panel shows the average data for this subject for the co-located condition (filled circles) and spatially-separated condition (filled squares). The difference between the two curves shows the amount of “unmasking” between the co-located and spatially-separated conditions.

The WIN test was conducted by routing the output of a CD-player through a Grason-Stadler Instruments 61 (GSI-61) audiometer in a double-walled, sound-attenuating booth. In the test booth, the subject’s head was located at a distance of approximately 1.5 meters from the speaker, where multi-talker babble was at a calibrated level of 75 dB(A), and the subject was instructed to listen to a female voice in the presence of competing noise saying monosyllabic words and to write down what she said. Subjects were instructed that the test would become more difficult as it went on and to
take a best guess when unsure of the word presented. Each subject was given a practice
list to orient them to the task prior to beginning the test conditions.

A total of four phonemically balanced 35-word lists were randomly assigned.
Each of the two WIN word lists were used for each spatial condition, with different list
randomizations. For the spatially-separated condition, the noise was fixed at the dial
setting 81 dB HL and the speech stimuli was routed through the second channel at 72 dB
HL. For the co-located condition, the noise was fixed at the dial setting of 80 dB SPL,
and the speech stimuli was presented through the second channel at 72 dB SPL.
Chapter IV: Results

Tone-in-Noise Detection

A 2 x 2 repeated measures ANOVA was performed to determine if detection thresholds for behavioral and physiological conditions were significantly different. Factors were test method (behavior and physiology) and phase condition (three levels: $S_oN_o$, $S_πN_o$, and $S_oN_π$). The effect of test method was not significant [$F(1,10) = 0.959, p = 0.351$]. However, the effect of phase condition was significant [$F(1.220, 12.201) = 9.321, p = 0.008$, partial $\eta^2 = 0.482$]. The test method X phase condition interaction was also significant [$F(1.333, 13.331) = 38.371, p < 0.001$, partial $\eta^2 = 0.793$]. Post-hoc comparisons indicated that detection thresholds for $S_oN_π$ were significantly lower than for $S_oN_o$ and $S_πN_o$. Mean detection threshold data for each phase condition are shown in Figure 6. As Figure 6 shows, mean detection thresholds for behavior follow expected trends. The average detection threshold for the homophasic condition ($S_oN_o$) is higher (poorer) than for the two antiphasic conditions. FFR detection thresholds for $S_oN_o$ and $S_oN_π$ are similar, whereas a much higher (poorer) FFR detection threshold is observed for $S_πN_o$. Follow-up ANOVAs for trends in behavioral and physiological detection thresholds were performed separately and are described below.
**Figure 6.** Detection thresholds for behavioral (filled symbols) and physiological (open symbols) thresholds. Errors bars are one standard error. Expected trends are observed for behavioral detection thresholds; FFR detection thresholds are significantly poorer for $S_{\pi}N_0$.

A follow-up one-way repeated measures ANOVA was conducted for behavioral detection threshold with a within-subjects factor of phase condition (three levels: $S_0N_0$, $S_{\pi}N_0$, and $S_{\pi}N_{\pi}$). The main effect of phase condition was significant [$F(2, 24) = 39.817$, $p<0.001$, partial $\eta^2 =0.768$]. As expected, behavioral detection thresholds for the antiphase conditions ($S_{\pi}N_0$ and $S_0N_{\pi}$) were significantly lower (better) than the homophase condition ($p<0.001$), consistent with a release from masking. Logistic fits to reconstructed psychometric functions of behavioral detection of tones-in-noise for each individual are shown in Figure 7. Mean detection threshold data for each phase condition are shown in Figure 6.
Figure 7: Logistic fits of reconstructed psychometric functions for each phase condition. Fits to individual data (thin lines) and average data (thick lines) are shown. The solid horizontal line at 0.707 represents threshold from the adaptive task; the dotted horizontal line at 0.5 represents chance performance. Better behavioral detection in the antiphase conditions is demonstrated by the average fits in the lower right panel, where the functions have shifted to the left of $S\omega N_0$. 
An additional follow-up one-way repeated measures ANOVA was conducted for FFR detection threshold for amplitude with a within-subjects factor of phase condition (three levels). The main effect of phase condition was significant \([F(1.15, 12.64) = 20.346, p < 0.001, \text{partial } \eta^2 = 0.649]\). Post-hoc tests indicate FFR detection thresholds were higher (poorer) in the \(S_\pi N_o\) condition compared to \(S_o N_o\) and \(S_o N_\pi\) \((p < 0.001)\): FFR detection thresholds for \(S_o N_o\) and \(S_o N_\pi\) were not significantly different \((p = 0.059)\). The higher (poorer) detection thresholds for the \(S_\pi N_o\) condition, suggests no physiological release from masking for this condition. FFR detection thresholds were equivalent in the \(S_o N_o\) and \(S_o N_\pi\) conditions. The similar detection thresholds for \(S_o N_o\) and \(S_o N_\pi\) suggests no or minimal physiological release from masking for this condition on average. Logistic fits to normalized FFR amplitude across SNR, for each individual, are shown in Figure 8. Comparison of the individual logistic fits in Figures 7 and 8 demonstrate that as SNR becomes poorer, behavioral detection and FFR amplitude become poorer respectively; stated in another way, similar trends for tone-in-noise detection are observed for both perception and physiology In addition, average logistic fits to behavioral and physiological detection thresholds are overlaid in Figure 9.
Figure 8: Logistic fits of normalized FFR amplitude by signal-to-noise ratio. Fits to individual data (thin lines) and average data (thick lines) are shown. Comparison of average fits in the bottom right panel demonstrates that, on average, no release from masking is evident from the normalized FFR amplitude data. Normalized FFR amplitude declined as SNR became poorer. FFR detection thresholds were defined as the lowest SNR with a present response.
Figure 9: Logistic fits to the mean reconstructed psychometric functions (solid lines) and logistic fits to the mean normalized FFR amplitude by signal-to-noise ratio data (dashed lines). Behavioral data indicate release from masking, while the average fits to normalized FFR amplitude indicate unmasking in the upper portions of the logistic fits.

Masking Level Differences

A 2 x 2 repeated measures ANOVA was performed to determine if masking level differences for behavioral and physiological conditions were significantly different. Factors were test method (behavior and physiology) and phase condition (two levels: $S_\pi N_\alpha$ and $S_\alpha N_\pi$). The effect of test method was significant [$F(1,10) = 81.485, p < 0.001$, partial $\eta^2 = 0.891$]. Likewise, the effect of phase condition was significant [$F(1,10) =$...
The test method X phase condition was also significant \([F (1,10) = 24.291, p = 0.001, \text{partial } \eta^2 = 0.708]\). Mean masking level difference data for each phase condition are shown in Figure 10. On average, the mean behavioral MLD was significantly larger (better) than the physiological MLD for the same phase condition. This effect was greatest for the \(S_{\pi}N_{o}\) condition in which a much greater difference (in dB) was noted between the size of the behavioral MLD and the physiological MLD.

**Figure 10.** Average masking level differences for behavioral (filled symbols) and physiological (open symbols) at 500 Hz. Errorbars are one standard error. FFR MLDs are significantly poorer than behavioral MLDs.

**Behavioral MLDs**

A follow-up repeated measures ANOVA was conducted for Masking Level Difference with a within-subject factor of phase condition (two levels: \(S_{\pi}N_{o}\) and \(S_{o}N_{\pi}\)). The main effect of phase condition was not significant \([F (1, 12) = 3.037, p = 0.107]\). Figure 10 summarizes the behavioral MLDs (filled symbols) and physiological MLDs.
(unfilled symbols). The average behavioral MLD for $S_{\pi}N_o$ was 10.03 dB (s.d. 4.96) and 8.29 dB (s.d. 4.09) for $S_oN_{\pi}$. This is an expected finding consistent with the behavioral MLD literature.

**Physiological MLDs**

A follow-up repeated measures ANOVA was conducted for Masking Level Difference with a within-subject factor of phase condition. The main effect of phase condition was significant [$F (1, 11) = 23.921, p < 0.001, \text{partial } \eta^2 = 0.685$]. However, a small FFR MLD was observed in most subjects in this data set for the $S_oN_{\pi}$ condition. Average FFR MLDs were 1.83 dB (s.d. 3.01) for $S_oN_{\pi}$ and -11.83 dB (s.d. 9.59) for $S_{\pi}N_o$. However, a much lower (poorer) FFR MLD was observed for the $S_{\pi}N_o$ condition, possibly due to phase-summation effects. This will be discussed in further detail in the discussion portion of the document.

FFR MLDs were significantly lower (poorer) compared to behavioral MLDs. On average, negative MLDs were observed for the $S_{\pi}N_o$ condition. Behavioral MLDs were significantly higher (better) than FFR MLDs. Behavioral data show a robust MLD for the two antiphasic conditions, suggestive of a “release from masking.”

**Relationship between Behavioral and Physiological MLDs**

Figure 11 shows scatterplots of behavioral MLDs and FFR MLDs to explore possible brain-behavior relationships. Filled symbols indicate an FFR MLD $> 0$ dB, open symbols indicate an FFR MLD $\leq 0$ dB. FFR MLDs were not significantly predictive of behavioral MLDs for either the $S_{\pi}N_o$ ($R^2 = 0.16, p = 0.201$) or the $S_oN_{\pi}$ condition ($R^2 =$
0.00, \( p = 0.969 \)). That is, individuals with smaller behavioral MLDs were not the same individuals with smaller FFR MLDs. However, several subjects had an FFR MLD greater than 0 dB for the \( S_oN_π \) condition, consistent with FFR unmasking as reported in Wilson and Krishnan (2005).

**Figure 11.** Scatterplots of FFR MLDs and Behavioral MLDs explore brain-behavior relationships. Filled symbols indicate an FFR MLD > 0 dB, open symbols indicate an FFR MLD < 0 dB. FFR MLDs were not significantly predictive of behavioral MLDs.

**Alternate Definition of FFR Detection Threshold**

Tone-in-noise detection thresholds were obtained behaviorally, as well as for the FFR. However, the two threshold estimates used different definitions. Behavioral detection thresholds focused on the 70.7\% correct point on the psychometric function, while FFR detection thresholds were defined as the lowest SNR at which a present response was obtained. FFR detection thresholds were also defined using the 0.707 normalized amplitude point from logistic fits to each individual’s data, allowing
physiological detection thresholds and FFR MLDs to be recalculated with an alternate definition more similar to that used in the perceptual task (see Figure 12). Using equivalent points on the functions for both behavior and physiology may provide a fairer comparison between these two types of detection threshold estimates.

Figure 12. Detection thresholds and masking level differences for behavioral (filled symbols) and physiological (open symbols) thresholds where FFR detection thresholds have been redefined as 0.707 normalized amplitude. Errors bars are one standard error.
Figure 13. Scatterplots of FFR MLDs and Behavioral MLDs, where FFR MLDs were based on 0.707 normalized FFR amplitude detection thresholds. Filled symbols indicate an FFR MLD > 0 dB, open symbols indicate an FFR MLD < 0 dB. Using the revised 0.707 FFR detection thresholds, FFR MLDs are not predictive of behavioral MLDs.

Raw FFR amplitude is affected by phase condition

FFR detection thresholds (see Figure 12) and examination of raw FFR amplitudes across phase conditions (Appendices A and C) indicate a general trend of lower raw FFR amplitude in S\(\pi\)N\(_o\) conditions relative to conditions where the 500 Hz tone, or signal, is in phase at each ear (S\(_o\)N\(_o\) and S\(_o\)N\(_\pi\)). This trend may indicate negative effects of phase summation, considering that the FFRs from the left and right ears are out of phase in S\(\pi\)N\(_o\) conditions. The lower right panel of Figure 14 demonstrates the average S\(\pi\)N\(_o\) raw amplitude across the various SNRs tested is reduced relative to the raw amplitudes of S\(_o\)N\(_o\) and S\(_o\)N\(_\pi\). Of note, is that at several SNRs (e.g., 8 and 16 dB SNR), only a small number of subjects were tested relative to 12 and 20 dB SNR at which most subjects were tested. Of particular note in Figure 14 in the bottom right panel is the seemingly “reduced” raw amplitudes observed at 16 and 8 dB SNR for S\(_o\)N\(_o\) and S\(_o\)N\(_\pi\). However,
these raw amplitudes at 8 and 16 dB SNR may not be truly representative as only a small number of subjects were tested there.

Figure 14. Raw FFR amplitudes across SNR and phase condition. Note that the range on the y-axis varies across the panels in this figure. The bottom right panel compares mean data and logistic fits to the mean data for each condition; data points have been slightly offset along the abscissa to minimize overlapping data points. Error bars are one standard error. FFR amplitude decreases as SNR becomes lower. FFR amplitude from the SπN₀ is, on average, less than half of that from the S₀N₀ and S₀Nπ conditions.

Amplitude differences may be calculated between the different phase conditions to examine if interaural phase differences of either the signal or the noise have an effect
on the robustness of FFR amplitude. Figure 15 shows FFR raw amplitude differences and data are consistent with $S_{\pi}N_0$ conditions having lower raw FFR amplitude values, while FFR amplitudes from the $S_{\alpha}N_0$ and $S_{\alpha}N_{\pi}$ are equivalent. Selection of SNRs during FFR recordings was an adaptive process, resulting in a low number of data points for some signal-to-noise ratios. To minimize the influence of SNRs where three or fewer subjects had data, these difference calculations were made using only SNRs where at least three subjects had been tested. Appendix A contains Figure A1, which shows these same amplitude difference calculations using all available data. We speculate that the reduced raw amplitudes observed for the $S_{\pi}N_0$ condition may be due in part to phase summation effects at the two ears. That is, the effect of having the signal interaurally phase-shifted (presented $180^\circ$ out of phase between the two ears), essentially created a phase cancellation effect for the signal resulting in reduced raw amplitudes across all subjects. The bottom right panel of Figure 15 illustrates negative effects of $S_{\pi}N_0$, mean differences are shown for SNRs where at least three data points were available; open symbols represent all available individual data, regardless of the number of data points at a given SNR.
Figure 15. Raw FFR amplitude differences between phase conditions. Top Row, average (filled symbol) and individual data (open symbols) for the SoNo – SπNo amplitude difference (left panel) and the SoNo – SoNπ amplitude difference (right panel); numbers along the bottom of the panel display how many subjects have data at each SNR. Bottom Row, mean amplitude differences are shown using only those SNRs that have data for at least 3 subjects. Bottom Left Panel, overlaid differences between SoNo-SπNo and SoNπ-SoNπ conditions. Bottom Right Panel, amplitude differences between the two antiphase conditions (SπNo – SoNπ) for average (filled symbol) and individual data (open symbols). FFR amplitude was essentially the same between SoNo and SoNπ conditions, where the 500 Hz toneburst was in identical phase across ears. However, the SπNo condition revealed an FFR amplitude decrement relative to SoNo or SoNπ.
Amplitude differences described in Figure 15 were found to predict behavioral MLDs for $S_N$ but not $S_N$. In an attempt to better understand the relationship between amplitude differences and the behavioral MLD, we compared these measures across all subjects, as well as to only those subjects with a behavioral MLD greater than 3 dB. The bottom left panel of Figure 16 shows that there is a strong correlation ($R^2 = 0.77, p = 0.021$) between the $S_N$ and $S_N$ FFR amplitudes at 12 dB SNR and for those subjects with a $S_N$ behavioral MLD larger than 3 dB. A fit to all behavioral MLDs for these same conditions failed to produce a significant correlation ($R^2 = 0.04$) as seen in the upper left panel of the figure. Similarly, a strong correlation is observed between FFR amplitude differences for the two antiphase conditions, $S_N - S_N$ ($R^2 = 0.99, p = 0.001$) and for those subjects with a behavioral $S_N$ MLD larger than 3 dB as shown in the bottom right panel of the figure. Again, the fit to all behavioral MLDs failed to produce a significant correlation ($R^2 = 0.14$) as seen in the upper right panel of Figure 16. However, the same predictive relationship between FFR amplitude differences and the behavioral MLD was not observed for the $S_N$ condition (see Figure B1 in the Appendix B); $R^2$ values were $\leq 0.05$. 
Figure 16. Bivariate scatterplots of 12 dB SNR FFR amplitude differences and behavioral $S_{\pi N_0}$ MLDs. In the bottom two panels, one subject (with a small behavioral MLD) was excluded from the correlation.

In a similar fashion, we compared these measures across all subjects, as well as to only those subjects with a behavioral MLD greater than 3 dB for the 20 dB SNR condition. The bottom left panel of Figure 17 shows that there is not a statistically significant relationship between the $S_{o N_0}$ and $S_{\pi N_0}$ FFR amplitudes at 20 dB SNR and for those subjects with a $S_{o N_0}$ behavioral MLD larger than 3 dB. A fit to all behavioral MLDs for these same conditions also failed to produce a significant correlation ($R^2 = 0.00$) as seen in the upper left panel of the figure. Similarly, there is a there is not a
statistically significant relationship FFR amplitude differences for the two antiphasic conditions, $S_\pi N_\pi - S_\pi N_o$ ($R^2 = 0.39, p = 0.136$) and for those subjects with a behavioral $S_\pi N_o$ MLD larger than 3 dB as shown in the bottom right panel of the figure. Again, the fit to all behavioral MLDs failed to produce a significant correlation ($R^2 = 0.00$) as seen in the upper right panel of Figure 17. Likewise, the same predictive relationship between FFR amplitude differences and the behavioral MLD was not observed for the $S_\pi N_\pi$ condition (see Figure B2 in Appendix B; $R^2$ values were $< 0.05$).

**Figure 17.** Bivariate scatterplots of 20 dB SNR FFR amplitude differences and behavioral $S_\pi N_o$ MLDs.
Figure 18 shows that raw S_oN_o FFR amplitude predicts the amount of amplitude reduction seen in the S_oN_o condition, suggestive of phase summation effects of the signal at the two ears. These data demonstrate that those subjects with the most robust S_oN_o amplitudes are the same subjects, with the largest amplitude reductions in the S_oN_o condition.

**Figure 18.** Bivariate scatterplots of raw amplitude difference (S_oN_o – S_πN_o) and raw S_oN_o amplitude for 12 dB SNR (left panel) and 20 dB SNR (right panel). FFR amplitude in the S_oN_o condition is significantly related to the difference between S_oN_o and S_πN_o. As FFR amplitude increases, larger amplitude differences are observed.

**Speech-in-Noise Data**

Figure 19 shows performance-SNR functions for the co-located (top left panel) and spatially-separated test condition (top right panel) for each individual subject. Of the fourteen subjects tested, only seven subjects reached performance poorer than 50% in the spatially-separated condition at the most challenging SNR. Because the signal-to-noise ratios corresponding to the 50% correct detection point could not be calculated for each
subject, the difference between percent correct at -8 dB SNR (the most challenging signal-to-babble ratio) was examined (Figure 19, bottom right panel).

Figure 19. Mean and individual data from the WIN conditions. **Top Row**, individual data for the co-located (left panel) and the spatially separated condition (right panel); **Bottom Row**, average WIN data for co-located condition (filled symbols) and spatially separated condition (open symbols) (left panel). The bottom right panel shows the percent correct difference (separated percent correct – co-located percent correct) between WIN conditions as a function of signal-to-babble ratio. In each panel, bold lines represent average data and the dashed line at 50% correct represents the WIN’s targeted point. Errorbars are one standard error.
Can Speech-in-Noise Understanding be Predicted from MLDs?

Simple linear regression was performed to determine if there was a predictive relationship between behavioral or physiological MLDs and the 50% point of the WIN. Additionally, these analyses were performed using the percent correct difference from the -8 dB signal-to-babble ratio of the WIN. Results showed that the 50% point on the WIN is not predicted by either the behavioral or physiological MLD ($p>0.05$). Additionally, the percent correct at -8 dB SBR (the most challenging signal-to-babble ratio) was not predicted by either the behavioral or FFR MLD ($p>0.05$). Stated differently, those individuals with the most robust behavioral and/or physiological release from masking were not necessarily the same subjects who demonstrated the most robust release from masking in the spatially-separated versus co-located conditions on the WIN test. Finally, performance on the WIN test was not predicted by FFR amplitude differences (e.g., $S_0N_o - S_{2}N_o$).
Chapter V

Discussion

The present study examined and compared behavioral and physiological masking level differences in young, normal-hearing listeners. The purposes of the study were: 1) to establish the feasibility of estimating physiological masking level differences using the frequency-following response (FFR), and 2) to characterize the relationship between behavioral and physiological measures of masking level differences (MLDs) in an effort to examine a possible brain-behavior relationship. Proposed hypotheses prior to data collection were 1) behavioral and physiological MLDs would be present for both the S\textsubscript{π}N\textsubscript{o} and S\textsubscript{o}N\textsubscript{π} conditions and 2) there would be a strong correlation between the behavioral MLD and FFR MLD. Those individuals with larger (better) behavioral MLDs were expected to have larger (better) FFR MLDs, and those individuals with smaller (poorer) behavioral MLDs were expected to have smaller (poorer) FFR MLDs. It was also hypothesized that subjects with a lower (better) 50\% point, in dB SNR, on the WIN test would be the same subjects with a higher (better) MLD on both the behavioral tone-in-noise detection task and the FFR.

Results showed a robust behavioral MLD for both antiphasic conditions (S\textsubscript{π}N\textsubscript{o} and S\textsubscript{o}N\textsubscript{π}). A small positive FFR MLD was observed in most subjects for the S\textsubscript{o}N\textsubscript{π} condition; however, a negative FFR MLD was observed in most subjects for the S\textsubscript{π}N\textsubscript{o} condition. FFR amplitude difference differences were predictive of the S\textsubscript{o}N\textsubscript{π} behavioral MLD but not for S\textsubscript{π}N\textsubscript{o}. Performance on the WIN test was not predicted by either behavioral or physiological MLDs.
Behavioral Masking Level Differences

A robust behavioral MLD for both antiphase conditions was observed in most subjects (10.03 dB (std. dev = 4.96) for SπN₀ and 8.29 dB (std. dev = 4.09) for S₀Nπ). It was hypothesized that a robust behavioral MLD would be present for both antiphase conditions (SπN₀ and S₀Nπ) and the results of the study demonstrate this. This finding is consistent with the classic behavioral MLD literature (Hirsh, 1948; Licklider, 1948; Webster, 1951). While the effect of phase condition was not statistically significant, a slightly larger behavioral MLD on average was observed for the SπN₀ condition. At 500 Hz, the SπN₀ condition (where the signal is phase-shifted by 180°) is frequently cited in the literature as producing the most robust release from masking (Pichora-Fuller & Schneider, 1991; Wilson et al., 2003). Wilson et al., (2003) states that on average the MLD for the SπN₀ is approximately 3 dB larger than for S₀Nπ. In the present study, the behavioral MLD between SπN₀ and S₀Nπ differed on average by 1.74 dB.

Physiological Masking Level Difference

On average, physiological MLDs did not reveal a robust release from masking, especially for the SπN₀ condition. In eleven of the twelve subjects tested for the FFR, a negative physiological MLD was observed for the SπN₀ condition. However, in seven of the twelve subjects tested for the FFR, a small positive release from masking was observed for the S₀Nπ condition. In the present study, the behavioral MLD was significantly larger on average than the physiological MLD for both phase conditions. This finding is consistent with that reported in Wong and Stapells (2004) in which they measured behavioral MLDs and physiological MLDs using the auditory steady-state
response. Wong and Stapells (2004) reported that all behavioral MLDs were larger than the ASSR MLD for the same condition. While the present study observed (on average) a positive FFR MLD for only the S\(_{\alpha}\)N\(_{\pi}\) condition, Wong and Stapells (2004) report a physiological MLD for the S\(_{\pi}\)N\(_{\alpha}\) condition only (and only for 7 or 13 Hz ASSRs, which have primarily cortical generators).

Similar to the results of this study, the mean psychoacoustic MLDs reported in Wilson and Krishnan (2005) were larger than the FFR MLDs for corresponding antiphasic condition. Like the present study, Wilson and Krishnan (2005) report a more robust FFR MLD for the S\(_{\alpha}\)N\(_{\pi}\) condition. However, unlike our study, Wilson and Krishnan (2005) do report a small physiological release from masking on average for the S\(_{\pi}\)N\(_{\alpha}\) condition. Methodological differences between the two studies (e.g., stimulus SNR selection may have contributed to these differences), as discussed in the literature review section of this document. Stimulus SNRs in their study may not have been equivalent across the phase conditions and they examined amplitude changes between phase conditions, rather than estimating physiological MLDs.

**Predictive Relationships**

*Did FFR MLDs predict behavioral MLDs?*

One of the purposes of the present study was to systematically evaluate the relationship (or lack thereof) between behavioral and physiological MLDs. Stated differently, we wanted to examine if a predictive relationship exists between these two measures. That is, does the magnitude of the FFR MLD predict the size of the behavioral MLD? In the present study, FFR MLDs were not predictive of behavioral MLDs.
Amplitude differences were highly predictive of the S\textsubscript{π}N\textsubscript{o} behavioral MLD, for subjects with a behavioral MLD larger than 3 dB; no physiological measures predicted the behavioral S\textsubscript{π}N\textsubscript{o} MLD.

Similarly, Wilson and Krishnan (2005) report no clear trend or relationship between the size of the psychoacoustic MLD and the FFR-MLD amplitude, although the brain-behavior relationship was not evaluated statistically. That is, individuals with larger behavioral MLDs did not necessarily have the largest FFR MLDs in either antiphasic condition.

**Was WIN predicted by behavioral or physiological measures?**

As stated previously, neither the 50% correct point on the WIN test nor the percent correct for the most challenging signal-to-babble ratio was predicted by either the behavioral or FFR MLD. Additionally, performance on the WIN test was not predicted by the FFR amplitude differences (e.g., S\textsubscript{o}N\textsubscript{o}-S\textsubscript{π}N\textsubscript{o}). Wilson and Weakley (2005) conducted a study to determine if a relationship exists between performance on a 500 Hz MLD task to monosyllabic word understanding task in multi-talker babble in young normal hearing listeners and listeners with hearing loss. The authors failed to find a systematic relationship between the two variables in the present study. That is, performance on a 500 Hz MLD task varied independently with the ability to understand monosyllabic words in the presence of multi-talker babble (Wilson & Weakley, 2005). Wilson and Weakley (2005) suggest that given the stimuli and methodology used in their study, the temporal processing information used to unmask a signal in an MLD paradigm is not systematically related to the auditory system’s ability or lack thereof to understand
speech signals in the presence of competing noise. Likewise, the results of the present study failed to find a systematic relationship between the size of the behavioral or physiological MLD and performance on the WIN test.

**FFR Amplitude Differences across Phase Conditions**

FFR amplitude followed the trend of behavioral P(C), decreasing as signal-to-noise became less favorable. However, on average FFR amplitudes from antiphase conditions were not enhanced relative to homophase amplitudes, FFR amplitudes from the $S_0N_0$ and $S_0N_\pi$ conditions were nearly identical, while significant amplitude reductions were seen for the $S_\piN_0$ conditions relative to $S_0N_0$ and $S_0N_\pi$ amplitudes. In the $S_\piN_0$ conditions, amplitude decrements were seen relative to $S_0N_0$ or $S_0N_\pi$ conditions, suggesting that scalp-recorded FFRs from humans reflect the summed response energy from each stimulated ear. When the FFR-eliciting stimuli are in opposite phases at the left and right ears, the scalp-recorded response apparently reflects a phase summation, or cancellation, effect that may result in reduced response amplitude.

It is unclear how much, if any, amplitude unmasking has been reported in the relevant FFR literature. Binaural processing has previously been examined using FFRs to evaluate if interaural timing and intensity differences are reflected differentially in FFR measures, but these studies have not included perceptual measures to compare behavioral and physiological findings (Ballachanda & Moushegian, 2000; Gockel, Muhammed, Farroq, Plack, & Carlyon, 2013). Ballachanda and Moushegian (2000) reported that the FFR recordings evoked by IIDs and ITDs were markedly different. The purpose of the Gockel et al., (2013) study was to see if the FFR recordings demonstrated evidence of
neural activity which is sensitive to interaural timing differences. That is, would the scalp-evoked FFR demonstrate adaptation specific to ITDs recorded in humans (Gockel et al., 2013). However, no evidence for ITD-specific adaptation in the FFR was found in this study. Wilson and Krishnan (2005) also used 500 Hz MLD stimulus conditions to elicit FFRs from young, normal-hearing humans. They reported enhanced amplitudes in antiphasic conditions relative to homophasic conditions. However, the stimulus selection procedure used in that study utilized stimulus signal-to-noise ratios that attenuated response amplitude by a certain amount. Stimulus signal-to-noise ratios were not always equal between homophasic and antiphasic stimulus conditions for each participant, so amplitude enhancement in antiphasic conditions may have also been influenced by variability in the acoustic SNR.

In the present study, trends across amplitude appear to be predictive of behavioral MLDs, at least for $S_{\pi}N_{o}$. Here, the data suggest a role for phase locking in behavioral masking level differences. Amplitude differences between phase conditions, $S_{o}N_{o}-S_{\pi}N_{o}$ and $S_{o}N_{\pi} - S_{\pi}N_{o}$, presumably reflect phase summation of neurophonic activity between left and right ear stimulation; the size of this amplitude difference is likely related to the quality of phase locking. Individuals with higher inter-ear neural synchrony would be likely to have higher $S_{o}N_{o}$ FFR amplitudes, and those individuals would also be likely to have larger degrees of FFR amplitude reduction in the $S_{\pi}N_{o}$ condition, where the 500 Hz stimulus is of opposite polarity in each ear. Amounts of FFR amplitude reduction in the $S_{\pi}N_{o}$ conditions may reflect the degree of inter-ear synchrony; individuals with higher levels of synchrony between the ears are those individuals that have larger amounts of FFR amplitude change from $S_{o}N_{o}$ to $S_{\pi}N_{o}$ and also have the largest behavioral $S_{\pi}N_{o}$
MLDs. R-squared values (see Figures 15, 16, and 17) indicate that this \( S_\pi N_0 \) phase summation is related to both raw FFR amplitude and \( S_\pi N_0 \) behavioral MLDs. Although behavioral and physiological MLDs are not strongly correlated, these trends in FFR amplitude suggest a role for phase locked neural activity being important in the percept of unmasking. A larger number of participants would help to clarify this relationship.

Neurophonic activity, such as that reflected in the FFR, has been associated with binaural processing of interaural time differences in human and animal data, as well as computational modeling. Carr and Konishi (1990) describe a neural circuity in the nucleus laminaris of barn owls, similar to the Coincidence Detector Model as first proposed by Jeffress (1948), which accounts for the precise detection of ITDs for sound localization in the horizontal plane.

Du, Huang, Wu, Galbraith, and Li (2009) reported unmasking in the amygdala of rats using the FFRs under MLD conditions, as well as a role of cortigofugal activity in brainstem unmasking suggesting a role for both in the processing of signals in the presence of noise. Neurophonic activity (periodic oscillations which closely mimic the frequency of the stimulus waveform, like the FFR) sometimes referred to as the sound analog potential (e.g., Funaniki, Ashida, & Konishi, 2011), has demonstrated that responses recorded from single units of barn owl nucleus magnocellularis resembling the FFR, is important for interaural time difference processing (e.g., Ashida, Funabiki, Kuokkanen, Kempter, & Carr, 2012). In addition, modeling of this sound analog potential indicates its quality of phase locking modulates the output of coincident detector neurons, which have been theorized to be important in models of binaural hearing. (Ashida, Funabiki, & Carr, 2013a; Ashida, Funabiki, & Carr 2013b). The role of
coincidence detection has received much attention in theories of binaural hearing (e.g., Jeffress, 1948; for a review see Grothe, Pecka, & McAlpine, 2010).

FFR amplitude differences between phase conditions may reveal a novel view into the how similar the left and right ear neurophonics are or how potential input to coincident detector neurons relates to behavioral measures of binaural processing. Neural encoding of ITDs changes from the inferior colliculus to the primary auditory cortex (e.g., Belliveau, Lyamzin, & Lesica, 2014), transitioning from phase-locked activity to rate-based representations. Therefore, while perceptual unmasking in MLD stimulus conditions may not directly rely on neurophonic activity, as reflected in the FFR, this type of neural activity is believed to influence (be important for) binaural processing in the central auditory system (Ashida et al., 2013a).

**Methodological Issues**

Several methodological issues with the present study should be considered and will be discussed in the section below. The FFR detection threshold was planned to be defined in 2 dB steps. However, due to time constraints, FFR detection threshold was often defined in 4 dB steps rather than 2 dB steps to ensure that testing could be completed for all three phase conditions. These alterations in how the physiological detection threshold was defined across subjects may have contributed to small changes in the definition of the FFR MLD.

Additionally, based on the criteria used to determine response absence or presence ($p < 0.05$), one subject had a no response obtained at the highest SNR tested (i.e., 20 dB SNR) for $S_oN_o$ and $S_oN_π$, and four different subjects had a no response obtained at the highest SNR tested for the $S_πN_o$ condition.
**Clinical Applications**

One of the most common listening complaints of older listeners is difficulty understanding speech in the presence of background noise (Pichora-Fuller & Schneider, 1992). Binaural hearing plays an important role in the ability to detect and understand speech in competing noise (Koehnke & Besing, 2001). In particular, interaural comparison cues (i.e., interaural intensity differences and interaural timing differences) provide listeners with crucial spatial and localization cues to assist in the detection of speech in difficult and reverberant listening situations (Koehnke & Besing, 2001). The behavioral MLD has been used commonly to examine aging effects on binaural hearing (Koehnke & Besing, 2001). The release from masking reflected in the antiphase conditions of the MLD demonstrates the auditory system’s ability to use these interaural comparison cues to unmask the signal from the noise (Wilson et al., 2003). Pichora-Fuller and Schneider (1991) found a significant difference between the size of the MLD in young versus older subjects, even when the effect of a minimal hearing loss in the older group was accounted for. It has been suggested that poorer MLDs in older listeners may be affected by the co-existing effects of advanced age and hearing loss (Koehnke & Besing, 2001). At the time of this dissertation, to our knowledge, there have been no systematic studies which compare behavioral and physiological measures of masking level difference across the lifespan. While it is speculated that speech-in-noise difficulties experienced by older listeners may stem from changes and declines in auditory processing as well as the cognitive processing of speech (Pichora-Fuller & Schneider, 1992), it has also been suggested that age-related changes/dysfunction at the level of the
auditory brainstem or cortex may contribute to these speech-in-noise difficulties independent of peripheral hearing loss (e.g., Frisina and Frisina, 1997).

Because the FFR can be used to assess the quality of neural phase-locked activity in the auditory brainstem (Worden & Marsh, 1968) measuring this type of response in older listeners (with and without peripheral hearing loss) may help to clarify if similar age-related declines are seen on a physiological measure of unmasking as seen in behavioral tone-in-noise detection. While the present study failed to find a systematic relationship between the size of the behavioral MLD and/or physiological MLD and performance on the Words-in-Noise test, the additional factors of hearing loss and advanced age may reveal more similarities between these measures than in young, normal hearing listeners. If so, it may have important implications for better understanding the hearing-in-noise difficulties experience by these listeners.

**Future Directions**

The question of the exact relationship between behavioral and physiological measures of unmasking generated in the auditory brainstem still remains, as well as how or if performance on these two measures affects one’s ability to understand speech in the presence of background noise. Future directions may include examining the relationship between these two measures in listeners across the lifespan (e.g., middle-age and older listeners), as well as those with peripheral hearing loss.

Examining FFR responses from a horizontal recording montage (e.g., earlobe-to-earlobe) should also be considered. Analysis of FFRs from a horizontal montage may reflect neural activity from lower, more caudal brainstem generators (Bidelmen, 2015)
and should be explored to see if the electrode montage has a differential effect on the relationship between behavioral and FFR MLDs. A more conservative detection algorithm could be considered (i.e., \( p \)-value <0.01) for determining FFR response absence and presence, like what was used in Wong and Stapells (2004). Testing at lower (more challenging) or higher (less challenging) SNRs could be considered to more accurately define physiological detection thresholds. Doing so may better approximate physiological detection thresholds in individuals who either have a present response at the lowest SNR and/or subjects who did not have a present response at the highest SNR tested.

**Conclusions**

(1) Robust behavioral unmasking observed in the two antiphasic conditions (\( S_\pi N_o \) and \( S_o N_\pi \)), are consistent with the published behavioral MLD literature.

(2) FFR amplitude decreased as SNR became poorer, following the same expected trend of behavioral tone-in-noise detection.

(3) Physiological FFR MLDs did not indicate a robust release from masking, especially for the \( S_\pi N_o \) condition. However, on average, FFR MLDs were positive for the \( S_o N_\pi \) condition.
Appendix A.

Figure A1. Raw amplitude difference calculations across all available data.
Appendix B.

**Figure B1.** Bivariate scatterplots of 12 dB SNR FFR amplitude differences and behavioral $S_oN_N$ MLDs.
Figure B2. Bivariate scatterplots of 20 dB SNR FFR amplitude differences and behavioral $S_0N_π$ MLDs.
Appendix C.

The figures below show individual data (in rows). In these double y-axis panels, the left y-axis shows $P(C)$ from the behavioral task and the right y-axis shows normalized FFR amplitude. Open symbols are behavioral data; filled symbols are FFR data. Phase conditions are plotted in separate columns. Panels on the far right show overlaid logistic fits for each individual.
Appendix D.

**Figure D1.** Scatterplots of FFR amplitude and FFR phase coherence across all subjects. Results show strong relationship across all phase conditions between the two analysis methods.
References


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