ABSTRACT

Title of Document:	INVESTIGATION OF FREQUENCY CHARACTERISTICS OF DPOAES USING SUPPRESSORS OF VARYING BANDWIDTH AND CENTER FREQUENCY PRESENTED IN A FORWARD MASKING PARADIGM.
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This study was designed to investigate the effect of the bandwidth and center frequency of narrowband noise suppressors presented in a forward masking paradigm on distortion product otoacoustic emission (DPOAE) level. Young adult female listeners with normal hearing participated. DPOAEs were recorded for two different pairs of primary frequencies (f1 = 1666 Hz, f2 = 2000 Hz and f1 = 3333 Hz, f2 = 4000 Hz) in an unsuppressed condition and three suppressed conditions for each of two experiments. In Experiment 1, the three noise suppressors were centered at the f2 frequency and had bandwidths selected to be equal to, narrower than, and wider than the estimated equivalent rectangular bandwidth (ERB) at that frequency. It was hypothesized that increasing the suppressor bandwidth from less than the estimated ERB to equal to the ERB would provide a significant increase in magnitude of suppression, but that a further increase in suppressor bandwidth beyond the estimated ERB would provide little if any additional suppression. In Experiment 2, the three noise suppressors had a constant bandwidth and were centered at the f2 frequency, ½ octave below the f2 frequency, and ½ octave above the f2 frequency. It was hypothesized that suppressors centered at the f2 frequency would cause greater suppression than suppressors centered above and below the f2 frequency. Results of Experiment 1 revealed a significant effect of the suppressors compared to the unsuppressed condition, but there were no significant differences between the suppressor bandwidths. Results of Experiment 2 support the hypothesis that a narrowband suppressor centered at the f2 frequency would have a greater suppressive effect than suppressors centered above or below the f2 frequency, at least for f2 = 2000 Hz. These results demonstrate that significant DPOAE suppression can be recorded using noise suppressors presented in a forward masking paradigm. Implications of these results for advancing understanding of the frequency tuning of the cochlea and the medial olivocochlear system are discussed.

INVESTIGATION OF FREQUENCY CHARACTERISTICS OF DPOAES USING SUPPRESSORS OF VARYING BANDWIDTH AND CENTER FREQUENCY PRESENTED IN A FORWARD MASKING PARADIGM

By

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Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Audiology
2007

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Dedication

This dissertation is dedicated to all of the friends and family who have supported and encouraged me throughout this process. Thank you to Mom, Dad, Kristen, Brian, and Philippe, who have learned more about DPOAEs than they ever wanted to. Thank you to my classmates Caroline, Christine, Kelly, Krystal, and Lauren for their friendship and constant encouragement.

Acknowledgements

The author gratefully acknowledges the contributions of the dissertation committee members: Sandra Gordon-Salant, Tracy Fitzgerald, Monita Chatterjee, Robert Dooling, Peter Fitzgibbons, and Edward Smith. Special thanks to Sandra Gordon-Salant and Tracy Fitzgerald for sharing their time and expertise as my dissertation advisors, and to Edward Smith and Robert Dooling for their contributions to the development of OpenDP. Thank you to all the participants who volunteered their time. This research was supported, in part, by a P-30 Core Center Grant awarded to the University of Maryland by NIDCD (NIH).

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Chapter 1: Introduction

The last half of the twentieth century saw considerable advances in our understanding of the function of the inner ear as a frequency analyzer, from both psychophysical and physiological perspectives. Békésy (1949) revolutionized understanding of the mechanical basis for cochlear frequency tuning with his discovery of the "traveling wave" motion of the basilar membrane. Using models and cadavers, he demonstrated that the location of basilar membrane displacement is related to the frequency of the incoming signal. However, a growing body of evidence suggested that the basilar membrane was capable of a wider dynamic range and a finer frequency resolution than could be accounted for with a passive linear mechanical model. This evidence led Gold (1948) to predict that cochlear function was not limited to passive displacement. Rather, he suggested that electromechanical activities added an "additional supply of energy" which would enhance the frequency selectivity of the basilar membrane. Thirty years would pass before Kemp's (1978) discovery of otoacoustic emissions (OAEs) would provide the first direct evidence of this active biological process within the cochlea.

Since Kemp's (1978) groundbreaking discovery, OAEs have been used as an important metric of cochlear function in both clinical and research domains. Because OAEs can be evoked in healthy normal cochleae, they have gained clinical popularity as a screening measure for hearing loss; however, clinical interpretation of OAE recordings currently remains limited to a gross indication of normal versus abnormal cochlear function. The full potential of OAEs as indicators of cochlear function remains unrealized, and considerable research effort has been devoted to describing and defining more complex and subtle properties of OAEs that may provide more valuable information about auditory system integrity. Because OAEs are evoked by stimuli significantly above the auditory threshold, there has been an increasing research emphasis on relating OAEs to suprathreshold aspects of auditory function rather than hearing sensitivity. Such knowledge could lead to development of more informative tests for both clinical and research purposes.

The outer hair cells, which have been identified as one potential source of OAEs in humans, are thought to be involved with active cochlear processes that sharpen frequency tuning in the cochlea (Davis, 1983). Because of this, OAEs have been investigated by many researchers as a possible measure of cochlear frequency resolution. The most common method used is the measurement of suppression tuning curves (STCs) using suppressor tones of varied frequency presented simultaneously with the OAE probe stimuli. Several researchers have tried to relate these OAE STCs to psychophysical tuning curves (PTCs) as an analogous measure of cochlear tuning, because both kinds of tuning curves exhibit similar shapes (e.g., Abdala, Sininger, Ekelid, & Zeng, 1996; Gorga et al., 2003). PTCs are measured using behavioral masking paradigms and are thought to provide information regarding the size and shape of the auditory filter for a given frequency. While it is clear from results of these studies that STCs have a strong relationship with frequency, it remains unclear whether they reflect characteristics of the auditory filter. Nevertheless, it seems likely that these measurements can convey valuable information about the excitation patterns of the basilar membrane in general and the outer hair cells in particular.

Cochlear outer hair cells do not work in isolation, but instead work as part of an efferent feedback loop involving the medial olivocochlear (MOC) system (Kim, Dorn, Neely, & Gorga, 2001; Sziklai & Dallos, 1993). It is believed that this feedback loop at least partially mediates active processing within the cochlea by influencing the activity of outer hair cells. Most efferent suppression paradigms focus on contralateral suppression of OAEs. Investigations have indicated that efferent suppression characteristics have a strong frequency dependence (e.g., Maison, Micheyl, Andeol, Gallego, & Collet, 2000). However, much remains to be explored about frequency characteristics of the efferent feedback system, and how they relate to frequency tuning within the cochlea.

OAE suppression tuning curves and some efferent suppression results are obtained using a specific type of OAE called distortion product otoacoustic emissions (DPOAEs), which are generated by the interaction of two stimulus tones. DPOAEs may be particularly suited to conveying information about frequency-related basilar membrane activity because the generation of the emissions has a strong dependence not only on the absolute frequency of the two stimulus tones but also on the frequency relationship between the two tones. Research has shown that a specific spectral relationship between the stimulus tones yields the largest DPOAE amplitudes (Brown, Gaskill, Carlyon, & Williams, 1993; Harris, Lonsbury-Martin, Stagner, Coats, & Martin, 1989), and this specific relationship is thought to reflect the conditions causing the maximum overlap of traveling waves on the basilar membrane. This overlap of activity on the basilar membrane is a likely source of the distortion energy that forms the basis of the emission (Shera & Guinan, 1999).

Evidence from previous investigations suggests a relationship between DPOAEs and cochlear tuning, though it is unclear the extent to which this relationship is mediated by the MOC system. The goal of the present study was to explore this relationship by examining frequency characteristics of DPOAE suppression using an ipsilateral forward masking paradigm. Noise suppressors of varying bandwidth or varying center frequency were presented prior to each pair of DPOAE stimulus tones in suppressed conditions, and resulting DPOAE levels were recorded and compared to levels recorded in the unsuppressed condition. Differences in DPOAE levels between suppressed and unsuppressed conditions were analyzed to determine the suppressor frequency characteristics that most effectively altered DPOAE levels. The assumption is that frequency-specific effects of the suppressor reflect either tuning characteristics along the basilar membrane, tuning characteristics of the MOC system that mediates outer hair cell activity along the basilar membrane, or some combination of the two. In Experiment 1, increases in the bandwidth of the suppressor were expected to cause related increases in the amount of DPOAE suppression for suppressor bandwidths falling within the frequency range most important for generating the nonlinear distortion component of DPOAEs. As the suppressor bandwidth exceeded that spectral area most involved in DPOAE generation, increasing suppressor bandwidth was expected to have little, if any, additional effect. In Experiment 2, suppressors centered at the frequency of the f2 stimulus tone were expected to yield more suppression than suppressors located above and below the f2 frequency. The results were expected to offer new insight regarding the frequency characteristics of DPOAE suppression.

Chapter 2: Review of the Literature

Cochlear Tuning and Auditory Filters

Considerable research effort has been devoted to investigating the spectral resolution properties of cochlear processing. The concept of auditory filters as a means to describe cochlear tuning has had a strong presence in the literature for many decades. Research has suggested that there are specific bandwidths that play an important role in the interaction and integration of signals in the peripheral auditory system. Fletcher (1940) inspired a flurry of research in this area with his conceptualization of "critical bands." He postulated that the peripheral auditory system functions as a series of overlapping bandpass filters centered at each point along the basilar membrane and governed by a critical bandwidth. Fletcher and many researchers after him have used a variety of psychoacoustic tasks to estimate the size and shape of these critical bands and related auditory filters (e.g., Greenwood, 1961; Houtgast, 1977; Patterson, 1976; Zwicker, Flottorp, & Stevens, 1957). While conceptual models and estimation methods have evolved due to these research efforts, the concept of auditory filters remains generally accepted as a useful model for describing frequency resolution within the cochlea.

In his classic paper describing his critical band concept, Fletcher (1940) presented data obtained using a band-widening experiment. He paired probe signals simultaneously with noise maskers of constant noise power density and varied bandwidths centered at the probe frequency. He observed that a listener's threshold for a sinusoid increased as the bandwidth of the noise masker increased, up to a certain point. Once the bandwidth of the masker was increased beyond this point, further increases in bandwidth did not cause further increases in the listener's threshold for the signal. These results have been replicated in several subsequent studies (e.g., Bernstein & Raab, 1990; Greenwood, 1961). Fletcher interpreted this abrupt change in masking effects to signify the edge of a critical bandwidth for frequency integration. He proposed that as the masker bandwidth is increased, more noise passes through a given auditory filter until the masker bandwidth equals the bandwidth of the auditory filter. Increasing the bandwidth of the masker beyond the width of the auditory filter was thought to have no effect as the extra noise would not be processed in the same auditory filter, and, therefore, would not affect detection of the probe.

It was originally assumed that the critical bandwidth measured with Fletcher's (1940) band-widening method provided a close estimation of the auditory filter. However, other researchers have reported wider estimates of the critical bandwidth (e.g., Zwicker, 1961; Zwicker et al., 1957). The concept of the critical band has continued to evolve, and more recent investigations have sought to estimate the "equivalent rectangular bandwidth" (ERB), defined as the width of a rectangular filter with a height equal to the peak of a filter that passes the same total power given a flat spectrum input (such as white noise). Moore and Glasberg (1983b) utilized data from six papers by other researchers to construct a formula to estimate the ERB for young, normal-hearing listeners at moderate sound levels, and they revised this formula based on additional data in 1990 (Glasberg & Moore, 1990).

The width of auditory filters has been proposed as a factor underlying distortion phenomena in the inner ear such as combination tones. It is thought that audible combination tones result from the interaction of the two stimulus tones on the basilar membrane, and stimulus tones must have a specific frequency relationship for their traveling waves to interact significantly (e.g., Greenwood, 1971; Smoorenburg, 1972). That two frequencies would interact in this way to produce additional audible tones suggests that they may be processed within the same auditory filter. Schroeder (1970) calculated that the phase behavior of combination tones showed a direct correspondence to estimates of critical bandwidth. It has been suggested that the same distortion generation process that underlies perceptual combination tones also governs the generation of distortion product otoacoustic emissions (Furst, Rabinowitz, & Zurek, 1988). It is therefore possible that the frequency characteristics demonstrated by DPOAEs and DPOAE suppression may be interpretable within the framework of auditory filters.

Otoacoustic Emissions: Background

The discovery of OAEs was immediately interpreted as evidence of an active biological process within the cochlea (Kemp, 1979). Evidence grew to suggest that OAEs occurred as a byproduct of the cellular mechanics responsible for the cochlear amplifier – specifically, the electromotile action of the outer hair cells (Davis, 1983). Research has established that outer hair cells change length following stimulation (Brownell, Bader, Bertrand, & de Ribaupierre, 1985), driven by a motor protein called prestin (Zheng et al., 2000). When many outer hair cells are stimulated in unison, their synchronous motion generates movement of the basilar membrane

(Ashmore, 1987; Brownell et al., 1985). Current understanding of outer hair cell activity suggests that their motile response to basilar membrane motion adds back energy to the peak of the traveling wave that is lost to viscous drag. This increases the velocity of endolymph flow over the stereocilia of the inner hair cells and increases their sensitivity and selectivity to acoustic input (Kemp, 2002). This process provides the additional source of energy theorized by Gold (1948) and is supported by evidence from numerous studies which have indicated that damage to outer hair cells yields poorer auditory sensitivity, with broader frequency tuning and abnormal growth of loudness (e.g., Khanna & Leonard, 1986a, 1986b; Liberman & Dodds, 1984; Ruggero & Rich, 1991). While outer hair cell electromotility appears to be of primary importance for the generation of OAEs in humans, evidence from animal studies has suggested that in the absence of outer hair cell motility, weak OAEs may still be recorded in response to high level stimuli due to nonlinear stereocilia transduction (e.g., Liberman, Zuo, & Guinan, 2004).

Not all energy generated by the outer hair cells joins the forward-moving traveling wave. Some of that energy travels in reverse to the base of the cochlea as fluid motion, is transmitted back through the middle ear as mechanical vibrations, and is converted by the tympanic membrane into low-level acoustic energy measurable in the ear canal as OAEs. Because OAEs are recorded in the ear canal, they are not pure representations of inner ear activity but rather have been modified by middle ear transmission properties that are unrelated to their inner ear generation. Nevertheless, it is believed that these emissions contain valuable information about the cochlear processes that created them (Kemp, 2002; Shera, 2004).

Current research supports the presence of two distinct mechanisms that generate evoked OAEs: nonlinear distortion and linear reflection. Nonlinear distortion is thought to result from the interaction of the cochlear amplifier with the peak of an incoming traveling wave along the basilar membrane; it is the OAE energy arising from this distortion that is attributed to outer hair cell activity. The linear reflection mechanism is conceptualized as irregularities in the impedance, anatomy, or mechanics of the basilar membrane that result in the reflection of energy backward out of the cochlea. It has been proposed that different evoking stimuli yield responses composed of different proportions of energy from distortion and reflection mechanisms (Shaffer et al., 2003; Shera, 2004; Shera & Guinan, 1999; Zweig & Shera, 1995).

Otoacoustic emissions can also be recorded without an evoking stimulus, and these are called spontaneous otoacoustic emissions (SOAEs). Estimates of prevalence vary somewhat, but according to one estimate, 64-81% of adult females with normal hearing have SOAEs, and 39-55% of adult males with normal hearing have SOAEs (Penner & Zhang, 1997). The mechanism of SOAE generation has been proposed as either linear reflections of mechanical oscillations of outer hair cells (Martin & Hudspeth, 2001) or standing waves within the cochlea that serve as their own continuous evoking stimuli (Shera, 2003). Individuals with SOAEs often have evoked OAEs with higher amplitudes compared to individuals with no SOAEs (Kulawiec & Orlando, 1995; Moulin, Collet, Veuillet, & Morgon, 1993).

Distortion product otoacoustic emissions. Distortion product otoacoustic emissions (DPOAEs) are a major class of evoked emissions that are used frequently for both clinical and research investigations. When two stimulus tones of different frequencies (called primaries) are presented simultaneously to the ear, emitted energy can be recorded in the ear canal at frequencies distinct from, but arithmetically related to, the frequencies of the stimulus tones. The primary stimuli are conventionally known as f1 and f2, and their levels are designated L1 and L2. When the primary tones are close enough in frequency, their traveling waves interact at their place of overlap along the basilar membrane, and this interaction generates much of the energy that is recordable in the ear canal. The emission at the cubic difference frequency, 2f1-f2, is typically the most robust DPOAE and is therefore most often used for clinical and research purposes. Numerous investigations have indicated that a f2/f1 ratio of approximately 1.2 and moderate, unequal levels of primaries (L1 > L2) maximize DPOAE amplitude (e.g., Gaskill & Brown, 1990; Harris et al., 1989; Hauser & Probst, 1991; Kummer, Janssen, & Arnold 2000).

Current research suggests that both the distortion and reflection mechanisms contribute to the generation of the 2f1-f2 DPOAE. Nonlinear distortion occurs at the basilar membrane location corresponding to the greatest overlap of the f1 and f2 traveling waves, generally considered to lie near the f2 frequency place, and much of this energy travels backward out of the cochlea. However, some energy from this region of overlap travels apically and peaks at the 2f1-f2 frequency location. A portion of this energy is reflected backward via the linear reflection mechanism, joining with energy from the distortion mechanism to be recordable in the ear canal (Shaffer et al., 2003; Shera, 2004). Research has suggested that the nonlinear distortion component generated near the f2 region of the basilar membrane provides the majority of the energy for the 2f1-f2 DPOAE, though this may vary across individuals and be influenced by stimulus levels and the f2/f1 ratio (Brown, Harris, & Beveridge, 1996; Knight & Kemp, 2000, 2001).

OAEs and Cochlear Tuning

Due to the frequency-dependent aspects of their generation, it has been suggested that DPOAEs contain important information about frequency-related phenomena and may even provide useful estimates of cochlear tuning (e.g., Abdala et al., 1996; Gorga et al., 2003). One common strategy for assessing frequency information conveyed by OAEs involves the presentation of a suppresser tone or noise designed to alter or interfere with the generation of emissions. If presenting a suppressor yields a reduction in OAE amplitude compared to a baseline measurement with no suppressor, it can be inferred that at least part of the frequency range affected by the suppressor is likely to be important for generation of the OAE. Investigating the frequency characteristics of the active processes that generate the OAEs may provide information about cochlear tuning, because the same processes that generate the OAEs are believed to enhance the sharp frequency resolution of the cochlea.

DPOAE suppression tuning curves (STC) have been presented as a means to investigate frequency-related aspects of cochlear activity. This paradigm involves the ipsilateral presentation of a pure tone suppressor (f3) simultaneously with the two primary tones (f1, f2). The frequency of the suppressor tone is varied. The level of the suppressor tone that reduces DPOAE amplitude by a criterion amount, usually 3 or 6 dB, is determined for each suppressor frequency and plotted as a suppression tuning curve (STC) (e.g., Abdala et al., 1996; Brown & Kemp, 1984; Gorga et al., 2003). Analysis of the STC typically includes the tip frequency, slope of the high- and low-frequency sides, and the Q_{10} ratio, which is a measure of the tuning curve width calculated by dividing the tip frequency by the bandwidth of the STC at 10 dB above the tip level (Pienkowski & Kunov, 2001).

In an early study, Brown and Kemp (1984) recorded DPOAE STCs in human participants and in gerbils. They investigated three different frequency pairs, with f2 = 1750 Hz, 3500 Hz, and 5800 Hz, and a frequency ratio (f2/f1) equal to 1.32, with L1 and L2 equal to 60 dB SPL. They reported that the frequency of the most effective suppressor tones approximated the f2 frequency and noted that higher frequency primary tones yielded more sharply tuned suppression tuning curves. They observed no evidence of equally effective suppression from tones similar in frequency to the DPOAE frequency of 2f1-f2. This provided early evidence that the 2f1-f2 frequency location on the basilar membrane was of secondary importance in the generation of the energy recordable in the ear canal. Brown and Kemp (1984) suggested that this OAE suppression paradigm yielded interesting results but implied that its utility was probably limited. Subsequent researchers, however, have proposed that DPOAE STCs can provide useful information about cochlear tuning (e.g., Abdala et al., 1996; Gorga et al., 2003).

DPOAE STCs have a sharp point, a steep slope on the high frequency flank, and a shallower slope on the lower frequency flank. Their shape narrows as primary frequency is increased and as primary level is decreased. For these reasons, it is often stated that their shape resembles neural tuning curves and psychophysical tuning curves (Abdala et al., 1996; Harris, Probst, & Xu, 1992; Kummer, Janssen, & Arnold, 1995). DPOAE suppression has also been found to have a frequency dependence similar to recordings of basilar membrane motion in animals (Ruggero & Rich, 1991; Ruggero, Rich, Recio, Narayan, & Robles, 1997) as well as to response growth measurements of single-unit rate-level functions (Schmiedt & Zwislocki, 1980). These similarities have led some researchers to suggest the use of STCs to provide objective and noninvasive measures of cochlear frequency tuning (e.g., Abdala, 1998; Abdala et al., 1996; Mills, 1998).

To investigate the effect of auditory system maturation on DPOAE STCs, Abdala et al. (1996) compared DPOAE STCs recorded from 15 normal-hearing adults and 16 healthy full-term neonates. Three f2 frequencies were investigated in adult participants (1500, 3000, and 6000 Hz), but only the higher two frequencies could be investigated in the neonates, because their physiologic noise was too high to allow recording of 1500 Hz. They used an f2/f1 ratio of 1.2, with L1 = 65 dB, and L2 = 50 dB. A third suppressor tone was varied in frequency from 1 octave below to ¼ octave above f2. The authors reported that no significant differences were found between the adult and neonate DPOAE STCs and suggested that the underlying cochlear tuning mechanisms responsible are mature by term birth. The tips of all STCs, indicating the most effective masker frequency, were located near f2. Tuning curves became sharper with increasing f2 frequency, with the lower frequency flank consistently having a shallower slope than the higher frequency flank. Overall, the authors concluded that the DPOAE STCs reflected the tuning characteristics of the cochlea, noting in particular how the narrow tuning curve width, asymmetric shape, and sharper tuning for higher f2 frequencies resemble PTC and neural tuning curves.

To explore further their relation to cochlear tuning, Gorga et al. (2003) compared DPOAE STCs recorded from the ears of normal-hearing and mildly hearing-impaired human participants. Using a single f2 frequency of 4000 Hz, they varied the levels of the primary tones. Suppressor frequency was varied from 1 octave below to ½ octave above the f2 frequency. They found that the tips of the STCs occurred close to f2, and they analyzed two estimates of cochlear tuning: Q_{10} and Q_{ERB} (the tip frequency divided by the ERB). They reported that lower levels of primaries required lower suppressor levels to achieve criterion suppression and yielded more sharply-tuned STCs based on the Q_{10} and Q_{ERB} values. As in other reports of DPOAE STCs, they also observed an asymmetric shape, with the lower frequency flanks having shallower slopes.

Statistical analysis indicated slightly broader tuning in the ears with mild hearing impairment compared to the ears with normal hearing, but the authors questioned whether this finding is meaningful, noting the presence of considerable overlap between the two groups. They suggested that while a mild hearing loss results in elevated thresholds, frequency tuning surrounding the elevated thresholds may not be significantly altered. They cited physiological data from single-unit and action potential recordings (Dallos & Harris, 1978; Liberman & Dodds, 1984) and forward masking action potential tuning curves (Gorga & Abbas, 1981) as evidence that mild degrees of hearing loss may not significantly decrease cochlear tuning. Furthermore, data from several animal studies (Howard, Stagner, Lonsbury-Martin, & Martin, 2002; 2003; Martin, Jassir, Stagner, Lonsbury-Martin, 1998) have shown that STCs measured following both temporary and permanent outer hair cell damage through exposure to noise or ototoxic drugs do not exhibit the characteristic broadening that one would predict based on research with neural tuning curves following cochlear insult (e.g., Liberman & Dodds, 1984; Ruggero & Rich, 1991). Some researchers have interpreted these results as evidence that DPOAEs do not convey useful estimates of cochlear tuning; however, Gorga et al. (2003) suggested another explanation. Only animals and human participants with outer hair cell damage mild enough to still provide relatively robust OAEs could be included in a study of OAE suppression. If the damaged outer hair cells can still generate OAEs, then perhaps they are still contributing to active cochlear processes such as frequency tuning (Gorga et al., 2003).

It is not surprising that the majority of studies have reported that suppressor tones near f2 yield the most reduction in DPOAE amplitude. The area of maximum overlap between the f1 and f2 traveling waves lies near the f2 frequency place, and this region of overlap is thought to provide the mechanism for the nonlinear distortion component of the DPOAEs (e.g., Pienkowski & Kunov, 2001). Research has consistently suggested that the 2f1-f2 frequency place does not play a primary role in the generation of DPOAEs measured in a STC paradigm (Abdala et al., 1996; Brown & Kemp, 1984). However, pure tone suppressors presented in the area of 2f1-f2 have been shown to eliminate fine structure of DPOAE responses, suggesting the 2f1-f1 region to be a secondary source in DPOAE generation. DPOAE fine structure describes the variability in DPOAE level observed when DPOAEs are recorded across a range of frequencies with very fine frequency resolution. Evidence from these studies suggests that the reflection source near 2f1-f2 may add to the distortion source in a constructive or destructive manner depending on the phase of the two components (e.g., Heitmann, Waldmann, Schnitzler, Plinkert, & Zenner, 1998; Konrad-Martin, Neely, Keefe, Dorn, & Gorga, 2001).

In addition to recording DPOAE STCs, Abdala et al. (1996) also recorded psychoacoustic tuning curves (PTC) for forward masked tones from a small subset of their adult participants. A comparison between the DPOAE STCs and the forward masked PTCs revealed that the PTCs had a narrower width (Q_{10}) and steeper slope. The authors suggest that this difference might be explained by the influence of off-frequency listening in psychophysical tasks. This difference in tuning curve shapes is noteworthy because it has been reported that PTCs measured in a forward masking paradigm are typically narrower than PTCs measured using simultaneous masking (Moore, 1978; Moore & Glasberg, 1981). Perhaps that phenomenon may have influenced their findings.

DPOAE STCs have been recorded exclusively using simultaneous suppressors. However, differences have been reported when using simultaneous versus forward masking techniques in psychoacoustic investigations (Moore, 1978; Moore & Glasberg, 1981). Therefore, the temporal parameters of the masking (OAE suppression) paradigm may have an important influence on OAE tuning results as well. For PTCs, Moore (1978) suggested that while forward masking effects are likely caused by neural activity in auditory channels stimulated by the probe, simultaneous masking effects may result from lateral suppression instead of, or in addition to, this neural activity. In this case, lateral suppression, or two-tone suppression, refers to an intracochlear swamping of probe activity by the masker and is different from OAE suppression, which refers to a decrease in OAE level in the presence of an additional stimulus (the suppressor). Due to the influence of lateral suppression, simultaneous masking may involve a separate process additional to the effect of the masker on excitation in specific auditory channels (Moore, 1978; Moore & Glasberg, 1981). Because the psychoacoustic results measured using behavioral forward masking paradigms yield different estimates of frequency tuning compared to psychoacoustic results measured with simultaneous masking, it would be useful to investigate this effect on DPOAE suppression using a forward masking paradigm.

While there are obvious fundamental differences between DPOAE suppression tuning curves and tuning curves measured using psychoacoustic masking or other physiologic paradigms, one difference in particular suggests that measures of cochlear tuning using OAEs may provide valuable information. Most psychoacoustic and physiologic measures of cochlear tuning involve measures made at or near threshold for certain stimuli. Using OAEs to estimate cochlear tuning could add to our knowledge of cochlear tuning for moderate level stimulation. Furthermore, unlike other physiologic measures, OAEs are non-invasive and therefore can be measured easily on humans. OAE recordings also do not require a behavioral response from the listener, which removes effects of attention, motivation, cognitive function, and central auditory processing.

There are some significant limitations of DPOAE STC results. When suppressor tones are presented simultaneously with the primary tones, it is possible that undesired interactions could occur between the suppressor and primary stimuli unrelated to the target DPOAE, either in the form of acoustic interactions, or as extraneous distortion energy produced by the interaction of a third tone on the basilar membrane. Presenting a suppressor that is temporally separated from the stimulus tones would reduce the likelihood of any unwanted interactions influencing the results. Additionally, all data discussed thus far were recorded using pure tone suppressors of varying frequency. The most effective suppressor tones, generally near the f2 frequency, provided criterion suppression at relatively low levels (around 40 dB) (Abdala et al., 1996; Gorga et al., 2003). As spectral distance from f2 increases, suppressor tones must be higher in level in order to generate sufficient spread of excitation to regions critical for DPOAE generation. However, it is unclear from a pure tone suppressor paradigm how much distance the spread of excitation must cover before it significantly impacts DPOAE generation. It is also unlikely that any pure tone suppressors affect the entire region of the basilar membrane responsible for the DPOAE, as this would likely require the use of suppressors with broader bandwidths. The use of a paradigm in which suppressor bandwidth is increased incrementally around f2 would provide useful information regarding the width of the spectral region most involved in DPOAE generation and suppression.

While it is generally agreed that the presence and suppression characteristics of DPOAEs convey useful information about outer hair cell integrity and cochlear function, the exact nature of this information and its relationship to cochlear frequency tuning is complex and not fully understood. Based on current evidence, it is likely that DPOAE STCs do convey unique and important information about frequency characteristics of cochlear processes. However, further research using novel paradigms is required to maximize the potential contribution of DPOAEs to our understanding of cochlear frequency tuning.

Influence of the MOC System on Outer Hair Cells and OAEs

Data from investigations of DPOAE STCs traditionally have been interpreted in terms of intracochlear activity. Absent from researchers' interpretations has been anything but the briefest mention of the potential influence of efferent mediation on DPOAE generation and suppression. But while the result of outer hair cell activity manifests itself as an intracochlear mechanical alteration, this phenomenon is at least partly under the control of the medial olivocochlear (MOC) efferent system. This cochlear-efferent feedback loop is thought to influence outer hair cell function (e.g., Kim et al., 2001; Liberman & Guinan, 1998), and the effects of the efferent system must be considered when exploring the topic of OAE generation and suppression. It is impossible to completely parse out purely intracochlear activity from MOC-mediated effects during ipsilateral suppression, particularly during simultaneous stimulus-suppressor presentations. While it is known that intracochlear activity attributed to the outer hair cells contributes to frequency tuning, it is less clear the extent to which this frequency tuning is preserved or influenced by the MOC system.

Influence of efferent feedback on outer hair cell activity is supported by anatomical structure. The outer hair cells receive a significant majority of efferent innervation to the cochlea, with efferent neurons from the MOC system synapsing directly on the outer hair cells (Liberman & Brown, 1986). The MOC system has both ipsilateral and contralateral projections, and stimulation to one ear affects the efferent mediation of outer hair cell activity in both ears (Kim et al., 2001). It is believed that the MOC efferent system moderates outer hair cell activity by inducing hyperpolarization to counteract the motile properties of outer hair cells and to alter the nonlinear gain they provide (Sziklai & Dallos, 1993). Data from animal studies suggest that the tonotopic frequency tuning in the cochlea is preserved through the efferent pathways, and efferent fibers synapse with outer hair cells in a very frequency-specific pattern (Brown, 1989; Liberman & Brown, 1986). Further evidence for the finely-tuned nature of MOC activity comes from neural tuning curves recorded from MOC fibers. These curves demonstrate sharp tuning similar to that found in afferent auditory nerve fibers (Brown, 1989; Liberman & Brown, 1986). Based on this physiological evidence, it seems that the fine frequency resolution sharpened by cochlear mechanics is preserved in the efferent feedback loop, at least in animal models.

Clearly, such invasive physiologic recordings are not possible in humans. Therefore, activation of the MOC system in humans must be measured using noninvasive methods. Suppression of OAEs is commonly used for this purpose, because alterations of the outer hair cell activity through efferent mediation yield measurable changes in OAEs (e.g., Collet, 1993; Collet, Kemp, Veuillet, Duclaux, Moulin, & Morgon, 1990). Data from animal studies have shown that applying electrical stimulation directly to the efferent fibers significantly affects OAE responses (Mountain, 1980; Siegel & Kim, 1982). In humans, however, activation of the MOC system is achieved using acoustic stimulation.

Studies of OAE suppression by the efferent MOC system have used not only DPOAEs but also transient evoked otoacoustic emissions (TEOAEs), a type of evoked emission elicited using brief clicks or tone pips (e.g., Berlin, Hood, Wen, & Kemp, 1995; Moulin, Collet, & Duclaux, 1993; Collet et al., 1990). A variety of suppressors have been used including broadband noise, narrowband noise, and pure tones (e.g., Berlin et al., 1995; Maison et al., 2000). Results from investigations of OAE suppression in humans are less clear than the physiologic evidence from animals regarding whether MOC effects exhibit sharp frequency tuning.

Results of at least one study have suggested that MOC effects evaluated via TEOAE suppression may be consistent with psychoacoustic estimates of the critical band and may therefore share similar characteristics with cochlear frequency tuning. Neumann, Uppenkamp, and Kollmeier (1997) recorded narrow-band TEOAEs in the presence of a contralateral broadband suppressor. They introduced a notch in the contralateral suppressor centered at the frequency of the TEOAE stimulus, and they incrementally increased this notch. The researchers used the decline in OAE suppression with increasing notch width to calculate the estimated ERB for each participant, then compared the ERB estimate derived with this OAE suppression paradigm with an estimate they derived from a psychoacoustic masking task using simultaneous notched noise. The two estimates of ERB derived using OAE suppression and psychoacoustic masking showed good agreement for the six participants with SOAEs, though the OAE experiments overestimated ERB for the three participants without SOAEs. The reasons for this relationship with SOAE presence were unclear, but the overall results suggest that the conceptualized “critical bandwidth” may play a role in frequency tuning beyond the level of the cochlea, including in the MOC system.

Some limited evidence for frequency selectivity of the MOC system has also been reported by Chéry-Croze, Moulin, and Collet (1993). They measured DPOAEs in the presence of contralateral narrowband noise of varying center frequency. They used very low DPOAE primary levels set 5 dB above each participant's DPOAE detection threshold and reported that for 2f1-f2 frequencies of 1000 Hz and 2000 Hz, maximum suppression occurred when the narrowband noise was centered near 2f1-f2. The tips of their published tuning curves appear fairly broad, and no tuning curve pattern was observed for 2f1-f2 frequencies of 3000 Hz and 5000 Hz. They interpreted their results as evidence for weakly frequency-specific MOC activation for 2f1-f2 frequencies of 1000 Hz and 2000 Hz, but not for 3000 Hz and 5000 Hz.

However, other evidence from OAE suppression in humans has suggested that MOC activity may be more broadly tuned than the intracochlear activity. Maison et al. (2000) compared effects of pure tone, narrowband noise, and broadband noise contralateral suppressors varying in level from 20 to 60 dB SPL on toneburst OAEs at 1000 Hz and 2000 Hz. Their 155 participants were divided into subgroups of 15-35 participants, and each group completed only some portions of the study. The authors reported that the broadband noise elicited the greatest amount of suppression, followed by the narrowband noise. The pure tone suppressors yielded the least amount of suppression and required the highest suppressor levels to achieve an effect. A comparison of the magnitude of suppression from various suppressor noise bandwidths (1/16, 1/8, 1/4, 1/2 and 1 octave) centered at the frequency of the toneburst revealed that the amount of suppression increased with increasing suppressor bandwidth. The researchers also analyzed the amount of suppression that occurred relative to the number of auditory channels affected by the contralateral suppressor. They calculated this relative suppression by dividing the amplitudes of the toneburst OAEs by the number of affected equivalent rectangular bandwidths (ERBs), which they estimated according to a formula suggested by Glasberg and Moore (1990). While overall suppression increased with increasing bandwidth, suppression per ERB decreased with increasing bandwidth. Greater amounts of suppression were achieved when the overall level of the suppressor was increased as bandwidth increased. However, even when overall suppressor level was held constant (corresponding to a decrease in the level-per-cycle), increases in bandwidth still yielded significant increases in suppression. The authors suggested that these findings are evidence of an effect of suppressor bandwidth separate from the effect of suppressor level, and they interpreted these findings according to the model of the peripheral auditory system as a series of bandpass filters. They proposed that the increase in the sum of across-channel activity with increasing bandwidth contributed more to overall suppression than an increase in within-channel input level. The increasing effectiveness with increasing bandwidth out to such wide bandwidths suggests that integration of MOC activation can occur over a wide range of frequencies, and this would indicate that MOC frequency tuning is fairly broad. Lilaonitkul, Backus, and Guinan (2002) have reported similar results using stimulus frequency otoacoustic emissions (SFOAEs), a type of evoked OAE in which the recorded emission is the same frequency as the evoking stimulus tone. They interpreted those results to mean that the MOC system does not show the fine frequency tuning present in cochlear activity. These results seem to contradict the sharp tuning curves recorded from MOC fibers in animals (Brown, 1989; Liberman & Brown, 1986). Further investigation is needed to clarify the degree of frequency tuning present in the MOC system and whether the frequency characteristics of MOC activity vary with the parameters of acoustic stimulation.

While the MOC influence is bilateral, it has been studied most often using a contralateral suppression paradigm to ensure that results are not influenced by the interaction of the simultaneous stimulus and suppressor tones (e.g., Collet et al., 1990; Puria, Guinan, & Liberman, 1996; Williams & Brown, 1997). This theoretically provides a purer measurement of the influence of the efferent pathways on outer hair cell function without confounding intracochlear influence. However, Berlin et al. (1995) directly compared suppression using ipsilateral, contralateral, and binaural noise. They presented all suppressors in a forward masking paradigm to ensure minimal acoustic interaction of the signal and suppressor in the ipsilateral condition in order to allow comparisons between the conditions. They recorded the amount of click-evoked OAE suppression obtained with noise of 408 ms duration presented in a forward masking paradigm ipsilaterally, contralaterally, and binaurally. The largest magnitude of suppression was observed in the binaural condition, with the contralateral condition providing the smallest magnitude of suppression.

This finding is consistent with recordings from animals suggesting that the ipsilateral MOC reflex is stronger than the contralateral reflex (e.g., Brown, 1989; Liberman & Brown, 1986). Additionally, anatomic and physiologic observations from animal models have found that twice as many olivocochlear neurons respond to ipsilateral stimulation as respond to contralateral stimulation (e.g., Liberman, Puria,

& Guinan, 1996; Maison, Adams, & Liberman, 2003). Similar anatomic observations are clearly not possible in humans, so OAE suppression paradigms may offer the best means of evaluating the relative strength of the MOC system in ipsilateral, contralateral, and binaural conditions. Therefore, while most OAE suppression experiments have used contralateral suppression due to convenience, more effort is needed to study ipsilateral suppression paradigms that could allow valid comparisons to contralateral and binaural conditions.

Time course of MOC system activation. The time course of efferent activity suggests that suppressive effects begin rapidly following the presentation of an acoustic signal. Evidence for this comes from studies of DPOAE adaptation, in which DPOAE stimuli effectively act as their own suppressors. This phenomenon has been shown to be related to efferent activity. Using DPOAE stimuli of 5.5 seconds duration, Kim et al. (2001) reported an average decrease in DPOAE level of 1.1 dB, with a range of .4 to 3 dB. Their data indicated both a fast and a slow adaptation component, suggesting two different mechanisms underlying the decrease in DPOAE amplitude. The fast component occurred at an average of 69 ms after stimulus onset and accounted for an average reduction of 0.65 dB. The slow component occurred at approximately 1.51 seconds after stimulus onset and resulted in an additional decrease of 0.4 dB. DPOAE level reached a steady state by 4.5 seconds; however, variability across individuals was noted in both the timing and the magnitude of the adaptation.

These findings support previous data recorded from cats by Liberman et al. (1996). They found that DPOAE adaptation in anesthetized cats included both fast (around 100 ms) and slow (around 1000 ms) components, with the slow component contributing a smaller amount of OAE amplitude reduction. Following olivocochlear section, most of the DPOAE adaptation was eliminated, suggesting the primary source of fast DPOAE adaptation to be the olivocochlear system. However, the slower adaptation component with the smaller magnitude remained, suggesting that this component originates from intracochlear distortion activity. This evidence from the time course of DPOAE adaptation in the absence of an additional stimulus may provide clues about the processes responsible for the decrease in OAE level when an additional suppressor is present.

Using ipsilateral, contralateral, and binaural forward masking paradigms, Berlin et al. (1995) investigated the effect of the silent interval duration between the offset of the suppressor noise and the onset of a four-click stimulus on TEOAE suppression. They found that the most suppression was seen for stimulus clicks that began within 5 ms of the offset of the noise. By recording the OAE level throughout the duration of the four-click series, they observed the greatest magnitude of suppression between 8 and 18 ms following the onset of the initial click. Interstimulus intervals greater than 50 ms resulted in little suppression. These results provide strong evidence that the amount of suppression decreases with increasing interstimulus interval. Berlin et al. (1995) interpreted their results as evidence of MOC effects.

Evidence suggests that the efferent MOC system plays an important role in OAE suppression and OAE adaptation. Given the apparent MOC mediation of outer hair cell activity, it is possible that MOC activation may influence the frequency tuning achieved by the active processing of the cochlea. Some evidence from previous studies of TEOAEs (Maison et al., 2000) and SFOAEs (Lilaonitkul et al., 2002) suggests that MOC activation may demonstrate broad frequency tuning, but other evidence using DPOAEs (Chéry-Croze et al., 1993) and TEOAEs (Neumann et al., 1997) is mixed. More work is needed to describe the frequency tuning of the MOC efferent system and its role in DPOAE suppression in order to help determine its influence on and distinguish its effects from cochlear tuning.

Summary

It has long been known that the cochlea acts as a highly tuned frequency analyzer. Psychophysical tuning curves and other behavioral and physiological measures have often been used to derive estimates of auditory tuning (e.g., Houtgast, 1977; Moore & Glasberg, 1981; Patterson, 1976). Research has established that cochlear frequency tuning is the result of basilar membrane motion that is enhanced by the activity of the outer hair cells. The outer hair cells are, in turn, influenced by the MOC system. The combined effects of these components can be observed through OAE suppression, and it has been suggested that certain suppression paradigms may provide valuable information about cochlear frequency tuning (e.g., Abdala et al., 1996; Gorga et al., 2003). DPOAEs may be a particularly useful type of OAE due to their strong dependence on not only the absolute frequencies, but also the frequency relationship, of paired stimulus tones.

Results from DPOAE STCs measured using ipsilateral pure tone suppressors of varying frequency indicate that the most effective suppressors are close in frequency to f2. As the suppressor tone is moved farther from the f2 frequency, its level must be increased in order to achieve criterion suppression. The resulting graphs resemble PTCs, and some researchers have proposed that STCs provide estimates of auditory filter characteristics (e.g., Abdala et al., 1996; Gorga et al., 2003). However, evidence from PTC investigations indicates that simultaneous and forward masking paradigms provide different estimates of cochlear tuning due to differences in intracochlear activity. It has been suggested that two-tone suppressive effects influence psychophysical tuning curves measured in the simultaneous condition (e.g., Moore, 1978), and it is possible that DPOAE STCs are similarly influenced.

Researchers have reported consistently that auditory stimulation provokes the efferent system to mediate intracochlear activity and that this efferent influence can be measured through OAE suppression (e.g., Berlin et al., 1995; Liberman et al., 1996; Maison et al., 2000; Williams & Brown, 1997). Because outer hair cell motility is thought to contribute to frequency tuning in the cochlea, it is possible that this efferent mediation contributes to cochlear frequency tuning. Most studies examining the effects of the MOC efferent system have not focused specifically on frequency characteristics, but combined results from several studies using contralateral suppression of evoked OAEs present mixed conclusions about the frequency tuning of MOC activity (Chéry-Croze et al., 1993; Lilaonitkul, et al., 2002; Maison et al., 2000; Neumann et al., 1997).

OAE suppression can be elicited with both ipsilateral and contralateral suppressors, and while there has been some evidence that ipsilateral suppressors yield greater suppressive effects than contralateral suppressors (e.g., Berlin et al., 1995), further research is needed in this area.

Some researchers have suggested that OAE suppression paradigms, particularly ipsilateral STCs, may convey useful estimates of cochlear frequency tuning (e.g., Abdala et al., 1996; Abdala, 1998; Gorga et al., 2003). Other researchers have investigated the frequency specificity of contralateral efferent suppression to evaluate frequency tuning of the MOC system (e.g., Chéry-Croze et al., 1993; Lilaonitkul et al., 2002; Maison et al., 2000; Neumann et al., 1997). It is well-accepted in the literature that MOC activation influences the movement of the cochlear outer hair cells, altering the nonlinear characteristics of the cochlear amplifier. However, much remains to be learned regarding the frequency tuning of the MOC system and whether it resembles the sharp tuning displayed by the cochlea. Most DPOAE suppression paradigms have used either ipsilateral, simultaneous, pure tone suppressors or contralateral, simultaneous, noise suppressors. There have been few investigations reported using a forward masking paradigm. DPOAE suppression recorded using ipsilateral noise suppressors of varying bandwidth and center frequency presented in a forward masking paradigm would begin to fill a gap in the literature and would provide new evidence to enhance understanding of this issue.

Chapter 3: Research Questions and Hypotheses

Experiment 1

The goal of the present study was to investigate the effect of suppressor bandwidth on DPOAE suppression using an ipsilateral, forward masking paradigm. In Experiment 1, suppressor center frequency was held constant while the suppressor bandwidth was varied. The experimental questions were:

1. Does ipsilateral presentation of narrowband noise utilizing a forward masking paradigm yield measurable DPOAE suppression?

   Hypothesis: Ipsilateral suppression of DPOAEs is measurable utilizing a forward masking paradigm.

   There have been no published reports of ipsilateral forward masked DPOAEs; however, Berlin et al. (1995) have reported measurable suppression in forward masked click-evoked TEOAEs, and they found slightly greater magnitudes of suppression in the ipsilateral compared to the contralateral condition. Evidence from the many OAE suppression studies utilizing a wide variety of recording paradigms has shown that OAE suppression is a measurable, repeatable phenomenon.

2. Does the magnitude of DPOAE suppression increase with increasing suppressor bandwidth?

   Hypothesis: A suppressor bandwidth that is equal to the estimated ERB will yield more suppression than a suppressor bandwidth that is narrower than the ERB. However, a suppressor bandwidth that is wider than the ERB will not result in significantly greater suppression than was achieved when the suppressor bandwidth equaled the ERB.

The procedure and the expected results are reminiscent of classic psychoacoustic investigations of theorized "critical bands" and the related concept of auditory filters (Fletcher, 1940). Broader suppressor bandwidths are expected to affect a greater number of auditory channels through the frequency region responsible for DPOAE generation and suppression. Evidence from DPOAE STCs indicates that this region is centered near the f2 frequency place (e.g., Abdala et al., 1996; Gorga et al., 2003). If the suppressor bandwidth begins to exceed the region most active in DPOAE generation, subsequent increases in suppressor bandwidth should cause little or no additional suppression.

3. Is there an effect of primary frequency on DPOAE suppression using noise suppressors of varying bandwidth?

    Hypothesis: There will be no effect of f2 frequency on DPOAE suppression recorded using this paradigm.

Investigations of DPOAE STCs have shown that STC width narrows with increasing f2 frequency (Abdala et al., 1996; Kummer et al., 1995). However, the bandwidths used in the present paradigm are based on equal percentages of the ERB estimated according to Glasberg and Moore (1990). Theoretically, the ERB reflects cochlear frequency tuning and therefore already accounts for differences between frequencies. If these differences are already included in estimates of the ERB, then no differences in the suppression pattern between the f2 frequencies should be expected.

Experiment 2

In Experiment 2, suppressor bandwidth was held constant while the suppressor center frequency was varied. Suppressors were centered at the f2 frequency and ½ octave above and below the f2 frequency. The experimental questions were:

1. Is there an effect of the center frequency of narrowband noise suppressors on the magnitude of DPOAE suppression?

    Hypothesis: There will be an effect of suppressor center frequency on the magnitude of DPOAE suppression. Specifically, the suppressor centered at the f2 frequency is expected to produce the greatest amounts of suppression compared to the suppressors centered ½ octave above and below the f2 frequency. Additionally, the suppressor centered below f2 is expected to yield more suppression than the suppressor centered above f2.

Evidence from DPOAE STCs indicates that the primary mechanism of DPOAE generation is located near the f2 frequency place, because the tip of the STC approximates the f2 frequency. As pure tone suppressors become more remote from the f2 frequency, they require significant increases in level to generate a criterion amount of suppression (e.g., Abdala et al., 1996; Gorga et al., 2003). In a study of simultaneous contralateral suppression of TEOAEs, Maison et al. (2000) reported that narrow bands of noise located closest in frequency to the toneburst yielded the greatest amount of suppression. The expected difference between suppressors centered above and below the f2 frequency is based on the reported shapes of DPOAE STCs demonstrating that suppressor tones lower in frequency than f2 are more effective suppressors than those higher in frequency than f2 (e.g., Abdala et al., 1996; Gorga et al., 2003).

2. Is there an effect of primary frequency on DPOAE suppression caused by narrowband suppressors of varying center frequency?

   Hypothesis: There will be an effect of f2 frequency on the amount of suppression. Specifically, suppressors centered ½ octave above and below the f2 frequency of 2000 Hz will yield greater amounts of suppression than suppressors centered ½ octave above and below the f2 frequency of 4000 Hz.

   Investigations of DPOAE STCs have shown that STC width narrows with increasing f2 frequency (Abdala et al., 1996; Kummer et al., 1995). This means that for higher f2 frequencies, suppressor tones must be presented at higher levels as they become farther from the f2 frequency in order to achieve criterion suppression compared to suppressors around lower f2 frequencies. Therefore, suppressors centered at ½ octave above and below an f2 frequency of 4000 Hz are expected to be less effective suppressors compared to suppressors centered ½ octave above and below an f2 frequency of 2000 Hz.

In general, results from these two experiments were expected to provide new information regarding the effects of frequency-related suppressor parameters on

DPOAE suppression and to contribute to the body of knowledge regarding frequency tuning within the cochlea and MOC system.

Chapter 4: Method

Participants

Participants were recruited from the University of Maryland student population through word-of-mouth. Participation was limited to females aged 18-35 years. These criteria were selected to create a homogenous sample, because previous research has shown subtle differences in DPOAEs recorded from males and females (Cacace, McClelland, Weiner, & McFarland, 1996). Additionally, evidence has suggested that DPOAEs and DPOAE suppression are affected by the listener's age (Dorn, Piskorski, Keefe, Neely, & Gorga, 1998; Kim, Frisina, & Frisina, 2002). Because hearing loss is known to affect the presence and amplitude of DPOAEs, all participants had normal hearing. Middle ear function was verified through immittance measures, because normal middle ear transmission is required for DPOAEs to reach the ear canal (Osterhammel, Nielsen, & Rasmussen, 1993). Participants had no history of severe middle ear pathology (e.g., otosclerosis, cholesteotoma) or reconstructive external or middle ear surgery, and their ear canals were free of obstructions that could interfere with probe placement and stimulus delivery. Prior to data collection, all participants were screened to ensure the presence of measurable DPOAEs using the same stimulus parameters as were used in the experimental paradigm. Seventeen participants volunteered for this study, and three were excluded from data collection because they did not meet all of the above inclusion criteria. These inclusion criteria will be discussed in further detail in the Preliminary Procedures section. The mean age of the 14 volunteers whose data were included was 24.6 years (range 22-32 years).

Stimuli and Suppressors

Two pairs of primary frequencies were used in both experiments: f1 = 1666 Hz, f2 = 2000 Hz, and f1 = 3333 Hz, f2 = 4000 Hz. Both primary pairs had an f2/f1 ratio of 1.2. The levels of the primary tones, L1 and L2, equaled 65 dB SPL and 55 dB SPL, respectively, for all conditions. The f2/f1 ratio and the levels of the primary tones were selected to maximize DPOAE amplitude based on the results of previous research (e.g., Gaskill & Brown, 1990; Harris et al., 1989; Hauser & Probst, 1991; Kummer et al., 2000). The duration of the primaries equaled 40 ms, including a 5 ms rise/fall time. This duration was chosen, based on pilot testing of several stimulus durations, to be sufficiently long to record a reliable DPOAE response. Additionally, informal pilot testing demonstrated that a duration of 40 ms was not so long as to obscure all suppressive effects due to the preceding noise. Each run to obtain a single data point (DPOAE level and corresponding noise level) consisted of 51 averages, and the three highest-energy averages were rejected during analysis of the run.

Noise suppressors were comprised of digitally bandpass-filtered white noise with digital filter skirt slopes greater than 120 dB per octave. Noise duration was 200 ms including 5 ms rise/fall times, because stimuli of this duration have been shown by previous investigations to be adequately long to yield suppressive effects (Liberman et al., 1996; Puria et al., 1996). Following the offset of the suppressor was a 5 ms silent interval (Δt). This Δt was selected in order to minimize acoustic interaction between the suppressors and the stimuli. Informal pilot testing suggested that a Δt of 5 ms yielded recordings with measurable suppression but less noise contamination than shorter Δt durations. Berlin et al. (1995) also note that a 5 ms silent interval is desirable in order to let the suppressor noise decay prior to stimulus onset. The bandwidth of the noise suppressors was varied in different conditions as described below. The level-per-cycle of the noise was held constant at 40 dB SPL in all conditions in both experiments. For Experiment 1, the range of overall suppressor levels was 60 dB SPL to 65.6 dB SPL for f2 = 2000 Hz and 62.9 dB SPL to 68.6 dB SPL for f2 = 4000 Hz. For Experiment 2, when bandwidth was held constant, the overall suppressor levels were 60 dB SPL for f2 = 2000 Hz and 62.9 dB SPL for f2 = 4000 Hz.

Experimental Equipment and Software

All stimulus/suppressor generation and DPOAE data collection were completed using OpenDP (Version 3.21), a custom program run through MATLAB (Version 7.2). The system hardware consisted of a personal computer (Hush Technologies), a Digital-to-Analog/Analog-to-Digital Converter (Tucker-Davis Technologies, Model RP2.1), and a probe driver-preamplifier with probe assembly containing two speakers and a microphone (Etymotics Research, ER10-C). Figure 1 presents a schematic diagram of the equipment used to generate and record the DPOAEs.

Preliminary Procedures

All testing took place in the Hearing Research Laboratory and Hearing Clinic located in LeFrak Hall at the University of Maryland, College Park. Participants were fully informed of all preliminary and experimental procedures before testing. A sample Consent Form is shown in Appendix A. This protocol was approved by the

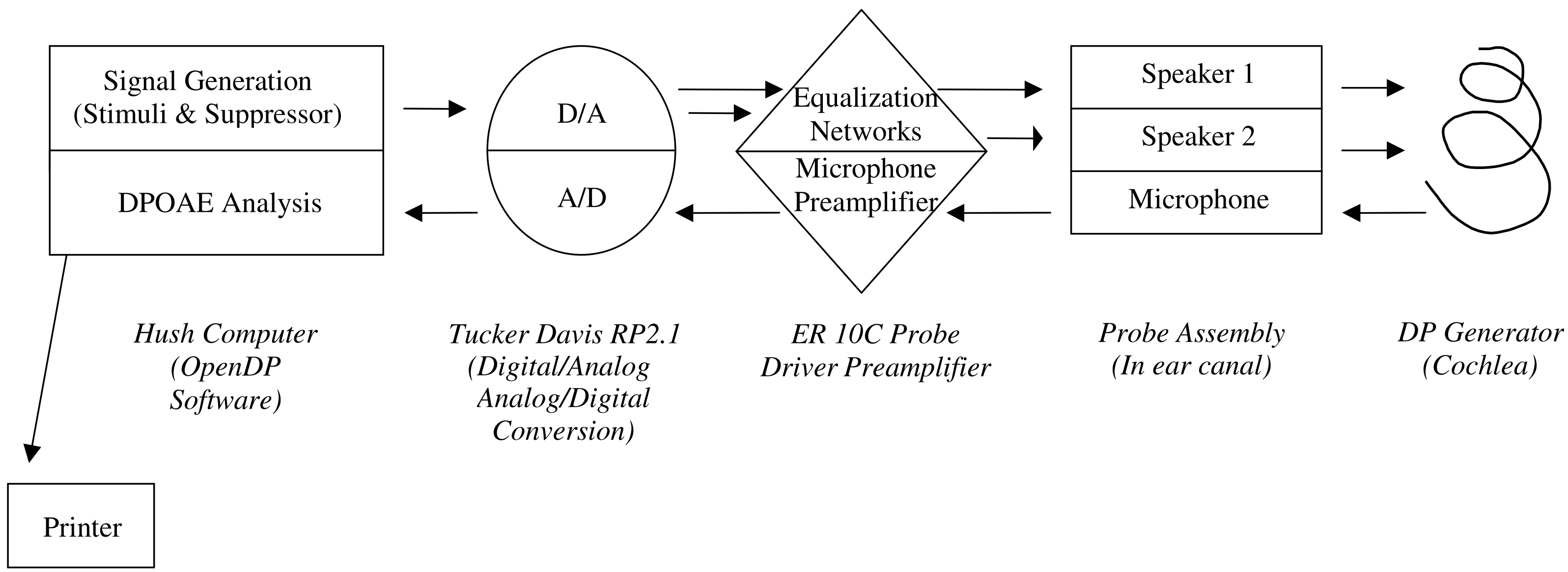

Figure 1. Schematic drawing of equipment set-up for DPOAE measurement.

Institutional Review Board at the University of Maryland, College Park (IRB # 05-0244).

Hearing status was determined through pure tone audiometry in a sound-treated booth using insert earphones (Ear Tone ER-3A), a bone oscillator (Radioear B-71), and a clinical audiometer (Grason-Stadler, Inc., GSI-61 or Interacoustics, AC40) calibrated according to the American National Standards Institute (ANSI) standard S3.6-2004 (ANSI, 2004). Because hearing loss can alter or eliminate DPOAEs (e.g., Gorga et al., 1997; Lonsbury-Martin & Martin, 1990), all eligible participants were required to have air conduction thresholds ≤ 20 dB HL for the audiometric test frequencies 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 3000 Hz, 4000 Hz, 6000 Hz and 8000 Hz. In addition, bone conduction thresholds were measured for octave frequencies from 500 Hz to 4000 Hz, and differences between air-conduction and bone conduction thresholds could not exceed 10 dB. The presence of even a small conductive loss might affect the recording of OAEs, because a conductive hearing loss would not only attenuate sound energy traveling into the ear, but would also attenuate OAE sound energy traveling back through the middle ear (e.g., Owens, McCoy, Lonsbury-Martin, & Martin, 1992). Participants completed a Hearing History Questionnaire (see Appendix B) with specific questions regarding their audiologic and otologic history. Otoscopy was used to verify that all participants' ear canals were free of excessive wax or debris accumulation, which could affect stimulus delivery and DPOAE recording, and to rule out any obvious outer ear or tympanic membrane pathology.

Tympanometry and acoustic reflex threshold testing were used to verify normal middle ear status, because measurement of DPOAEs can be significantly affected by middle ear transmission properties (Plinkert, Bootz, &Voßieck, 1994; Zhang & Abbas, 1997). These measurements were made using a clinical immittance unit (GSI-33 Middle Ear Analyzer) calibrated according to the ANSI standard S3.39-1987 (R2002) (ANSI, 2002). Peak-compensated static admittance was required to fall within 0.3-1.5 mmhos for a 226 Hz tympanogram; these values represent the 90th percentile range recorded from a population of young adults with normal hearing reported by Roup, Wiley, Safady, and Stoppenbach (1998). Tympanometric peak pressure was required to be between -50 and +25 daPa. This was chosen as a conservative range based on research demonstrating that middle ear pressure ≤ -100 daPa can affect the recording of OAEs (e.g., Trine, Hirsch, & Margolis, 1993). Acoustic reflex thresholds were recorded ipsilaterally and contralaterally for 500, 1000, and 2000 Hz pure tones and were required to be elicited at levels less than or equal to 100 dB HL. This upper limit reflects the 90^{th} percentile cutoff values of the normative data reported by Silman and Gelfand (1981) and Gelfand, Schwander, and Silman (1990). Acoustic reflex thresholds for broadband noise (125-4000 Hz) were recorded ipsilaterally. Individuals with thresholds < 62 dB HL were excluded from the study to ensure that any experimental findings of DPOAE amplitude reduction in the presence of a noise masker could not be attributed to the action of the acoustic reflex. The highest overall levels of suppressor noise used were 65.6 dB SPL in the 2000 Hz f2 condition and 68.6 dB SPL in the 4000 Hz f2 condition. Using the recommended reference equivalent threshold sound pressure levels (RETSPLs) for

2000 Hz and 4000 Hz, the levels of these suppressors were converted from dB SPL (used by OpenDP) to dB HL (used by the GSI-33 clinical immittance unit) (ANSI, 2004). The overall levels of the highest suppressors converted into dB HL were 56.6 dB HL for both f2 frequency conditions. Therefore, 62 dB HL served as a conservative criterion to ensure that included participants would not have acoustic reflex thresholds to broadband noise near the levels of the suppressor noise.

Thirteen of the 14 participants were screened for the presence of spontaneous OAEs using the Otodynamics ILO88 OAE Analyzer System. Synchronized SOAEs were recorded using click levels of 60 dB SPL and the default 260 averages. The measurement was performed twice to ensure repeatability of SOAEs. To be considered present, an SOAE had to be visibly above the surrounding noise floor and visible in both recordings. The frequencies and levels of SOAEs that met these criteria were recorded. Nine of the 14 participants had one or more SOAEs, four participants had no SOAEs, and SOAE screening of one participant could not be completed due to time constraints.

The presence of measurable DPOAEs was verified prior to data collection by recording unsuppressed DPOAEs for f2 = 2000 Hz and f2 = 4000 Hz using OpenDP with the same primary stimulus parameters as used during data collection. In order to ensure that the DPOAEs were adequately above the noise floor to yield reliable amplitudes, the DPOAE signal-to-noise ratio (SNR) of these initial recordings was required to be ≥ 6 dB. Both ears were screened for DPOAEs, and the ear with the greater amplitude DPOAEs was selected for data collection. Four right ears and ten left ears were tested.

As stated previously, a total of 17 participants volunteered for this study. Three participants were excluded from data collection based on the preliminary inclusion criteria described above; one participant had an acoustic reflex threshold for broadband noise < 62 dB HL, and two participants had unsuppressed DPOAEs which did not exceed the mean noise floor by at least 6 dB at either f2 frequency. Further information about the 14 participants who qualified for the study, including age, ear tested, pure tone thresholds at 2000 Hz and 4000 Hz, and frequencies of SOAEs (if present) can be found in Table 1.

Experimental Procedures

During the experimental measures, participants were seated comfortably in a chair facing a television and watched a movie with closed-captioning and without sound. During data collection, participants were instructed to remain still and quiet.

Two experiments were conducted, and two f2 frequencies were tested for each experiment; therefore, there were four experiment/f2 frequency combinations (Experiment 1/f2 = 2000 Hz, Experiment 1/f2 = 4000 Hz, Experiment 2/f2 = 2000 Hz, and Experiment 2/f2 = 4000 Hz). In both experiments, DPOAE data were obtained in an unsuppressed condition (no noise suppressor) and in three noise suppressor conditions, for a total of four conditions per experiment. A minimum of 12 runs was recorded for each condition, resulting in a minimum of 48 runs collected for each experiment/f2 frequency combination (four conditions x 12 runs each). As stated previously, each "run" to measure a single data point (DPOAE level and corresponding noise level) was obtained by collecting 51 averages.

Table 1

Demographic and preliminary audiometric data for the 14 participants included in data analysis

Participant Number	Age	Ear Tested	Pure Tone Threshold 2000 Hz	Pure Tone Threshold 4000 Hz	SOAEs Frequency (Hz) if present	
1	26	Left	5	0	891 1514	2319 2478
2	24	Left	0	5	Absent	
4	23	Left	5	0	1111	
6	25	Left	5	-5	Absent	
7	28	Left	0	0	854	891
8	22	Right	0	5	977 1062 1172 1538 1648	1929 2478 2637 3870
10	24	Left	5	5	Not tested	
11	23	Left	0	0	1306	1404
12	32	Right	5	15	Absent	
13	23	Left	-5	0	1526 1807	2002
14	26	Left	0	0	Absent	
15	22	Right	5	5	2539	
16	24	Left	-5	0	1672	
17	23	Right	5	0	793 1135	1355 1538

To begin testing for a particular experiment/f2 frequency, an ER10-14A or ER10-14B foam probe tip (size selected to best fit each individual ear canal) was placed on the ER-10C probe assembly and fitted into the participant's ear canal. Before beginning data collection, the ear canal response to the two primary tones was obtained to ensure an adequate probe fit. Once the probe fit was deemed acceptable (based on agreement of ear canal responses to chirps played from each transducer), collection of all data for that particular experiment/f2 frequency combination was completed.

After the minimum of 48 runs was recorded, the data were converted into graphical displays of each run. These displays were visually inspected for obvious noise contamination. If visual inspection suggested that more than two runs per condition had evidence of significant amounts of noise, additional runs were recorded. The canal response to the primary tones was then obtained a second time. The plots of the two canal responses were visually compared to ensure that the probe fit remained stable throughout the session. Participants were given a short break before beginning testing for another experiment/f2 frequency combination.

When possible, all preliminary and experimental measures were completed during a single session approximately 2.5-3 hours in length, with the order of Experiments (1 or 2) counterbalanced and the order of f2 frequencies (f2 = 2000 or 4000 Hz) within each experiment counterbalanced. However, some participants completed data collection in two sessions scheduled within approximately one week.

Experiment 1. This experiment evaluated the effect of suppressor bandwidth on the amount of DPOAE suppression achieved when the suppressor was presented in an ipsilateral forward masking paradigm. DPOAEs were recorded with no suppressor and in the presence of suppressor noise of three different bandwidths centered at the f2 frequency. Suppressors were centered at the f2 frequency because considerable research evidence has suggested that the primary mechanism of DPOAE generation is located near the f2 frequency place (e.g., Brown et al., 1996; Knight & Kemp, 2000; 2001). The three suppressor bandwidths included a bandwidth equal to 42% of the ERB, a suppressor bandwidth equal to the ERB, and a suppressor bandwidth equal to 158% of the ERB. The ERB at each f2 frequency was estimated using the equation suggested by Glasberg and Moore (1990): ERB = $24.7(4.37f + 1)$, where f is f2 frequency in kHz. For f2 = 2000 Hz, the suppressor bandwidths were 100 Hz, 240 Hz, and 380 Hz. For f2 = 4000 Hz, the suppressor bandwidths were 193 Hz, 460 Hz, and 727 Hz. As discussed previously, none of these suppressors resulted in overall sound pressure levels likely to elicit an acoustic stapedial reflex contraction in listeners with normal hearing (Margolis & Popelka, 1975). None of the suppressor bandwidths overlapped with the f1 or 2f1-f2 frequencies.

All of the 14 volunteers who met the criteria for participation were tested in Experiment 1. Ten volunteers participated in data collection for both f2 = 2000 Hz and f2 = 4000. Three additional volunteers participated in data collection for f2 = 4000 Hz only, because they did not meet the DPOAE inclusion criterion for f2 = 2000 Hz. Therefore, data were collected from a total of 13 participants for f2 = 4000 Hz. One participant provided data for f2 = 2000 Hz only, because data collection was terminated early at her request, and she was unable to return to complete data collection for f2 = 4000 Hz. Therefore, data were collected from a total of 11 participants for f2 = 2000 Hz.

DPOAEs were recorded for the minimum of 12 runs for the unsuppressed condition and for each of the three suppressor conditions, for a minimum total of 48 runs for each pair of primary frequencies for each participant. The order of all stimulus presentations was randomized within each set of primary frequencies. The order of primary frequencies tested was counterbalanced between participants. After all runs were recorded for one set of primary frequencies, the participant was given a short break. Prior to data collection for the second pair of primary frequencies, the probe was re-fit using a new probe tip to ensure a stable probe fit throughout the duration of testing.

Experiment 2. The goal of the second experiment was to evaluate the effect of noise suppressor center frequency on the magnitude of DPOAE suppression. Noise suppressors equal to 42% of the ERB for each f2 frequency were used. The suppressor bandwidths were 100 Hz and 193 Hz for the f2 frequencies of 2000 Hz and 4000 Hz, respectively. Suppressors were centered at the f2 frequency and at ½ octave above and ½ octave below the f2 frequency. For f2 = 2000 Hz, the suppressor center frequencies were 2000 Hz, 2828 Hz, and 1414 Hz. For f2 = 4000 Hz, the suppressor center frequencies were 4000 Hz, 5656 Hz, and 2828 Hz. For noise suppressors above or below the f2 frequency, there was no spectral overlap with either the f1 or f2 primary tones or the 2f1-f2 distortion product frequency.

Of the 14 individuals who qualified for the study, 12 participated in Experiment 2. Ten volunteers participated in data collection for both f2 = 2000 Hz and f2 = 4000. Two additional volunteers participated in data collection for f2 = 4000 Hz only, because they did not meet the DPOAE inclusion criterion for f2 = 2000 Hz. Therefore, data were collected from a total of 12 participants for f2 = 4000 Hz and from a total of 10 participants for f2 = 2000 Hz.

DPOAEs were recorded for a minimum of 12 runs for the unsuppressed condition and for each of the three suppressor conditions, for a minimum total of 48 runs for each pair of primary frequencies for each participant. The order of all stimulus presentations was randomized within each pair of primary frequencies, and the order of primary frequencies tested was counterbalanced between participants. Following completion of data collection for one pair of primary frequencies, participants were given a short break. In order to ensure a stable probe fit throughout the duration of testing, the probe was re-fit using a new tip prior to stimulus presentation for the second pair of primary frequencies.

Chapter 5: Results

Preliminary Assessment of Data Quality and Trends Over Time

A minimum of 12 runs was collected for each participant in each condition, and additional runs were recorded for some participants if significant noise contamination in more than two runs per condition was suspected based on brief visual inspections of each DPOAE plot. Most participants demonstrated runs that were acceptable (criterion for acceptable runs is explained below), and example data from one such participant are shown in Figure 2**.** This participant showed stable DPOAE levels and noise levels across runs and a high signal-to-noise ratio (the amount by which the DPOAE level exceeds the noise level). Data from a few participants showed drifts to higher or lower levels over time, but the changes were very small, and there was not a consistent pattern for any of the experiments. Data from eight participants showed these relatively stable patterns in Experiment 1, f2 = 2000 Hz, seven participants fit this category in Experiment 1, f2 = 4000 Hz, six participants fit this category for Experiment 2, f2 = 2000 Hz, and five participants fit this category in Experiment 2, f2 = 4000 Hz.

Several participants had very few, if any, good runs in one or more conditions. In these cases, noise contamination was observed in the form of highly variable DPOAE and noise levels within at least one condition, and/or runs in which the level of the noise exceeded the level of the DPOAE. The quality of the runs and the variability of DPOAE and noise levels had no apparent relationship with each participant's observed behavior and movement during data collection. Figure 3

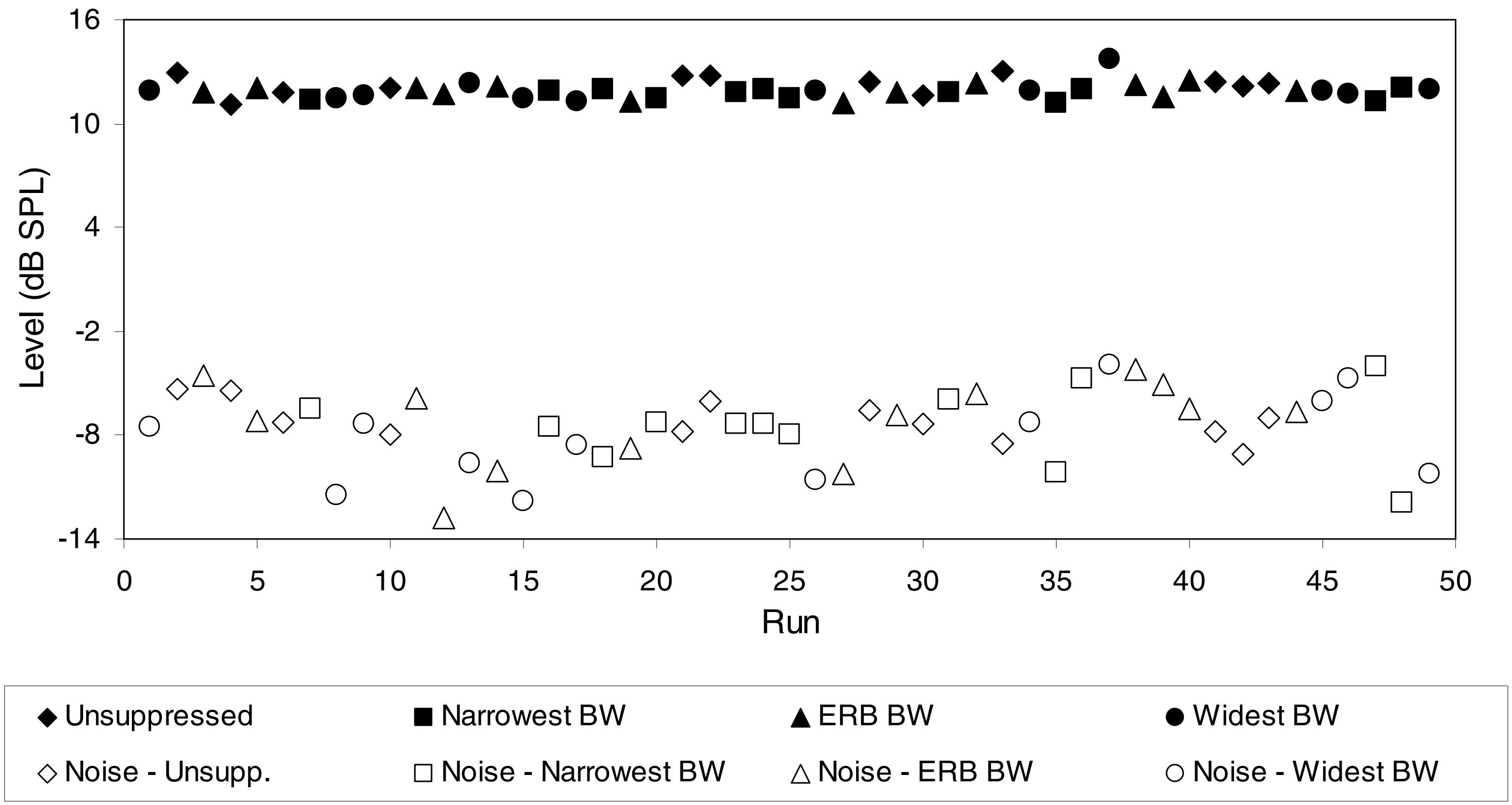

Figure 2. Example data from a participant with stable DPOAE and noise levels and high signal-to-noise ratios throughout data collection in Experiment 1, f2 = 4000 Hz. Shaded symbols show each DPOAE level and open symbols show the corresponding noise level for the four suppressor conditions over the 48 runs collected.

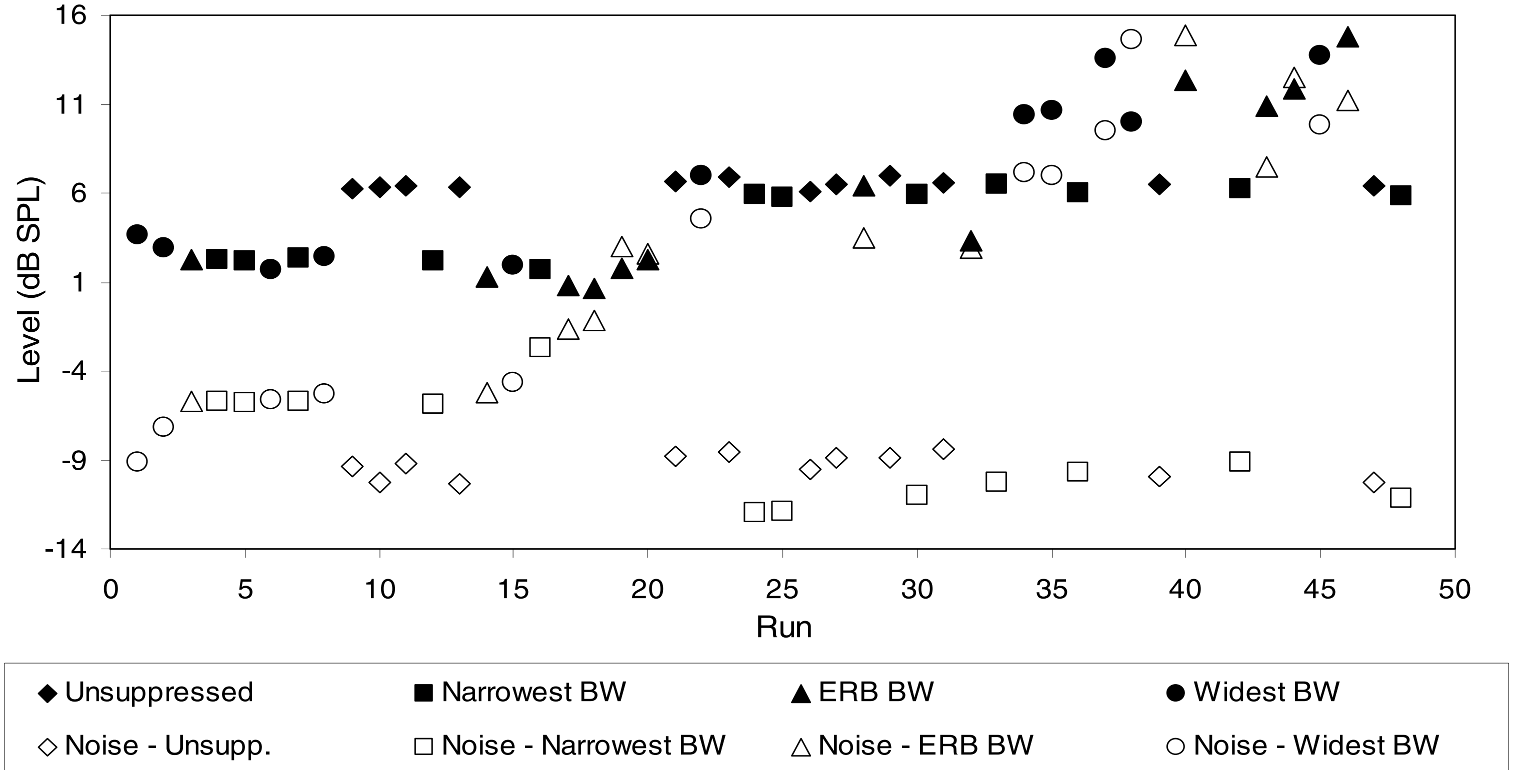

Figure 3. Example data from a participant with highly variable DPOAE and noise levels and poor signal-to-noise ratios in many runs in Experiment 1, f2 = 4000 Hz. Shaded symbols show each DPOAE level and open symbols show the corresponding noise level for the four suppressor conditions over the 48 runs collected. Data from this participant were ultimately excluded from data analysis.

shows data from a participant with highly variable DPOAE levels and noise levels with poor signal-to-noise ratios in many runs for all suppressed conditions throughout the duration of data collection. This category describes one participant in Experiment 1, f2 = 2000 Hz, two participants in Experiment 1, f2 = 4000 Hz, one participant in Experiment 2, f2 = 2000 Hz, and three participants in Experiment 2, f2 = 4000 Hz. These data were not included in analysis based on the criterion described below.

A third subset of participants had stable DPOAE and noise levels during a portion of data collection but unstable DPOAE and/or noise levels during a different portion of the data collection. Data from one such participant are shown in Figure 4. For this participant, the DPOAE and noise levels were stable with high signal-to-noise ratios throughout most of the early and middle portions of data collection but became increasingly unstable with decreased signal-to-noise ratios during the later portion of data collection. This category describes two participants in Experiment 1, f2 = 2000 Hz, four participants in Experiment 1, f2 = 4000 Hz, three participants in Experiment 2, f2 = 2000 Hz, and four participants in Experiment 2, f2 = 4000 Hz.

To minimize the influence of noise contamination on data analysis, a criterion was used to identify "clean" runs: a DPOAE level (in dB SPL) greater than 6 dB + 1 s.d. above the mean noise floor. The first five runs that met this criterion in each condition were used in data analysis. However, for participants whose data met the criterion only for later runs in some conditions, only corresponding later runs were used in all conditions to ensure that data from similar periods of time were compared. Similarly, in a very few cases, the randomized presentation order resulted in the first run in one condition occurring after the first five runs in another condition. In these

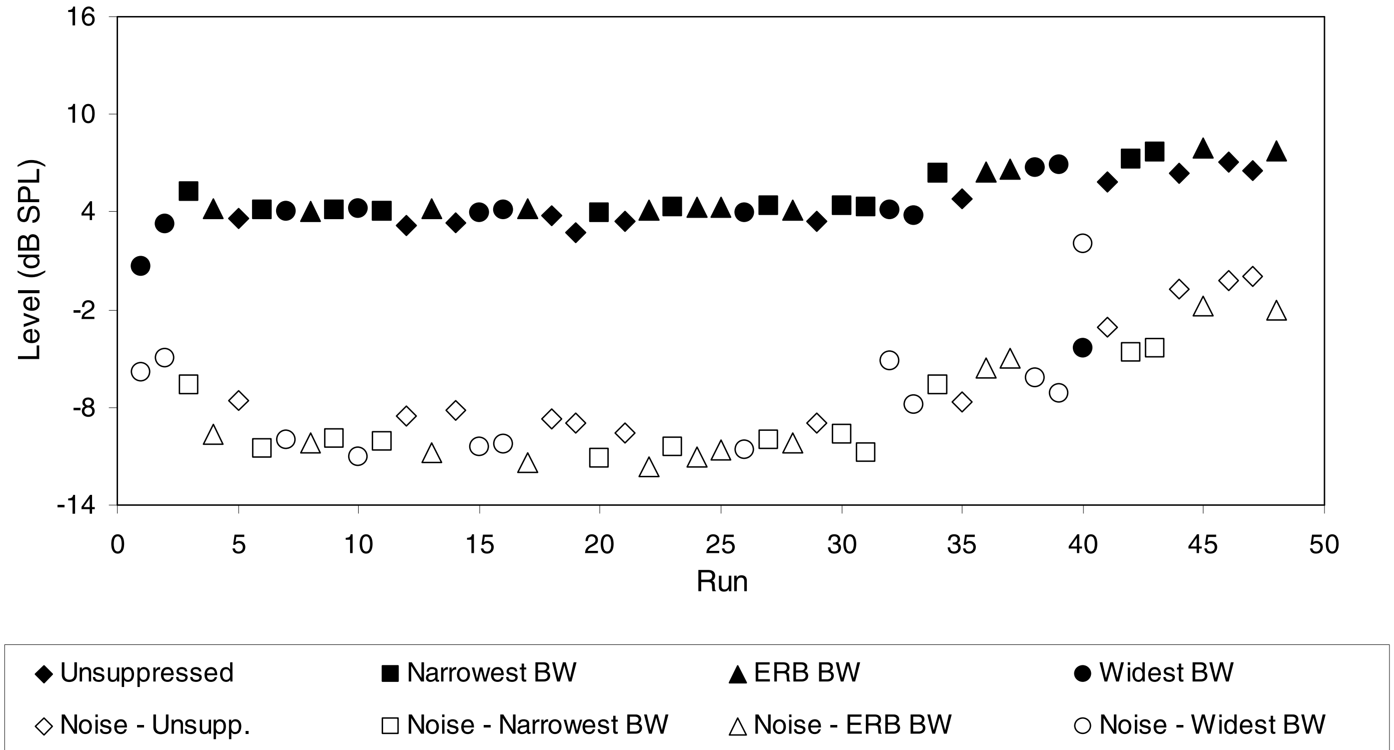

Figure 4. Example data from a participant with stable DPOAE and noise levels and high signal-to-noise ratios throughout most of the early and middle portions of data collection but increasingly unstable DPOAE and noise levels with decreasing signal-to-noise ratios during the later portion of data collection in Experiment 1, f2 = 4000 Hz. Shaded symbols show each DPOAE level and open symbols show the corresponding noise level for the four suppressor conditions over the 48 runs collected.

limited cases, the first five runs overall (regardless of condition) were skipped, and the five runs in each condition that were selected for data analysis began with overall run number six; this resulted in all analyzed runs in all conditions being recorded during the same period of time while maintaining the randomized presentation order. By ensuring that the subsets of data points used in analysis were recorded during similar periods of time, the potential effects of any trends in DPOAE and noise levels over time were minimized.

Several participants did not have five runs in every condition that met the criterion for inclusion in data analysis, and data for these participants were dropped for all conditions within an f2 frequency. Table 2 illustrates the data available from each qualifying participant in both experiments in each f2 frequency condition. Black squares indicate no available data (participant did not qualify for data collection at that f2 frequency or declined to participate in that part). Squares that are crossed off indicate data that were collected but dropped from analysis due to an insufficient number of runs meeting the criterion for inclusion in data analysis. Four participants provided usable data for both experiments at both f2 frequencies. For the data used in the analysis, the mean DPOAE and noise levels in the unsuppressed conditions for both f2 frequencies in Experiment 1 and Experiment 2 are given in Table 3.

The Statistical Package for Social Sciences Software (SPSS) for Windows GradPack, version 13.0 was used for data analysis. Data were analyzed using general linear models (multivariate ANOVA and repeated measures designs). Findings of significant main effects of condition were followed with a priori planned contrasts of

Table 2

Data from each participant used in analysis

Participant	Ear	Exp 1		Exp 2	
		2000 Hz	4000 Hz	2000 Hz	4000 Hz
1	L	✓	✓	✓	☒
2*	L	✓	✓	☒	☒
4	L	✓	✓	✓	✓
6*	L	✓	✓	✓	☒
7	L	✓	✓	✓	✓
8	R	✓	☒	✓	✓
10†	L	■	✓	■	✓
11	L	✓	✓	✓	✓
12*	R	✓	☒	✓	✓
13	L	☒	✓	✓	✓
14*	L	■	✓	■	✓
15	R	■	✓	■	■
16	L	✓	✓	✓	✓
17	R	✓	■	■	■
Total # with usable data		10	11	9	9

Note. Check marks (✓) indicate data used in analysis. Black squares indicate no available data (participant did not qualify for data collection at that f2 frequency or declined participation in that part). Crossed squares indicate data that were collected but dropped from analysis because fewer than five runs met the criterion for "clean" runs (DPOAE levels that exceeded the mean noise + 1SD by at least 6 dB). (*) denotes participants without SOAEs. (†) denotes the participant for whom SOAE data were not recorded.

Table 3

Unsuppressed DPOAE and noise levels (means, standard deviations, minimum, maximum) in dB SPL for f2 = 2000 Hz and 4000 Hz in Experiments 1 and 2

	Experiment 1				Experiment 2			
	f2 = 2000 Hz		f2 = 4000 Hz		f2 = 2000 Hz		f2 = 4000 Hz	
	DPOAE Level	Noise Level	DPOAE Level	Noise Level	DPOAE Level	Noise Level	DPOAE Level	Noise Level
Mean	9.9	-3.8	9.9	-8.0	11.2	-4.2	9.5	-8.2
Standard Deviation	3.7	2.8	2.8	3.0	2.0	2.3	4.0	3.9
Minimum	1.2	-8.0	3.3	-12.9	8.8	-7.6	2.4	-14.6
Maximum	13.7	.6	13.5	-2.3	14.8	-.2	16.4	-2.0

suppressor conditions. Helmert planned contrasts were selected to investigate differences between conditions, because the Helmert contrasts specifically evaluate whether the significant differences observed in the data match the hypothesized pattern of significance. Any significant main effects of run were explored using post hoc paired sample t-tests with Bonferroni correction. Data that were not spherical according to Mauchly's test of sphericity were analyzed using the Greenhouse-Geisser correction.

Experiment 1

Experiment 1 was designed to investigate the effect of suppressor bandwidth on ipsilateral forward-masked DPOAE suppression. DPOAE levels and noise levels obtained from participants were analyzed to determine the effect of f2 frequency, suppressor condition (no suppressor, and three suppressors varying in noise center frequency), and run.

Effect of f2 frequency. Only seven participants had data for both f2 frequencies in Experiment 1. Initially, data from this subset of participants were analyzed so that f2 frequency could be included as a condition in analysis. The mean DPOAE levels and noise levels obtained in the four suppressor conditions for both f2 frequencies from the seven participants are shown in Figure 5 across each of the five runs (panels a – e) and averaged across all runs (panel f). These data were analyzed using a repeated measures design with three within-subject factors: suppressor condition (four levels – no suppressor, narrowest BW suppressor, ERB BW suppressor, widest BW suppressor), f2 frequency (two levels - 2000 Hz and 4000 Hz), and run (five levels - five runs per condition). The examination of data across

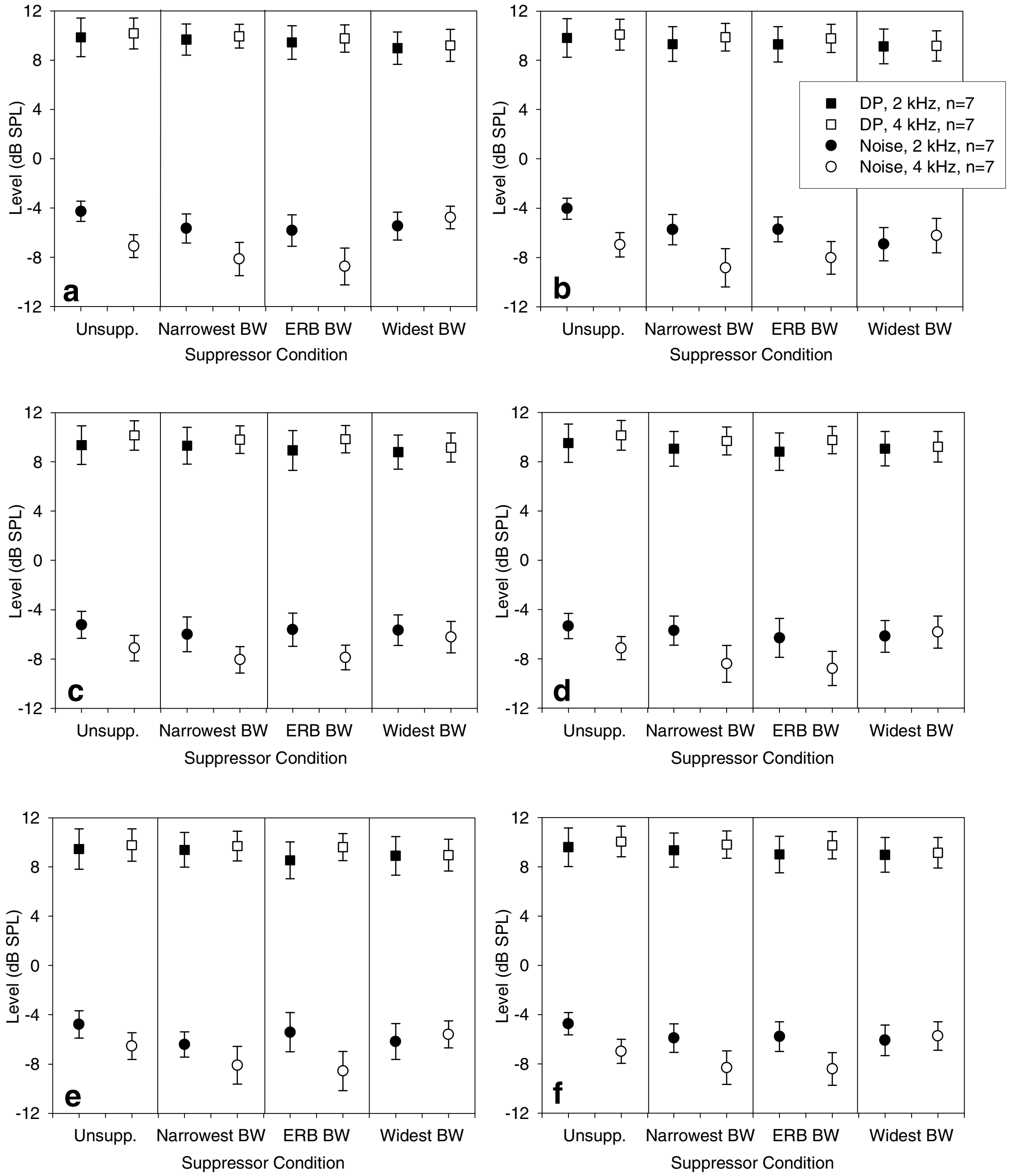

Figure 5. Mean DPOAE levels and noise levels are shown for the subset of seven participants who provided usable data for both f2 = 2000 Hz (filled symbols) and f2 = 4000 Hz (open symbols) in Experiment 1. Mean levels are shown for the four suppressor conditions in each individual run used in analysis (panels a – e) and averaged across the five runs (panel f). Error bars represent one standard error of the mean.

run is somewhat artificial; the data points were taken at different points in time for each individual depending on the random presentation order and the particular runs in each condition that met the selection criterion. Nevertheless, this examination of run is useful for identifying any trends over time within the data included in analysis. The main effects and interactions of these factors were investigated using a Bonferroni confidence interval adjustment to correct for multiple comparisons. Tests of within-subjects effects showed no significant main effect of f2 frequency [$F(1,6) = .843$, $p > .05$], a significant main effect of suppressor condition [$F(3,18) = 3.542$, $p < .05$], and a significant main effect of run [$F(4, 24) = 4.338$, $p < .01$]. There were no significant interactions between these factors [f2 frequency by suppressor condition: $F(3, 18) = 1.762$, $p > .05$; f2 frequency by run: $F(4, 24) = 1.175$, $p > .05$; suppressor condition by run: $F(12, 72) = .957$, $p > .05$, and f2 frequency by suppressor condition by run: $F(12, 72) = 0.524$, $p > .05$].

To ensure that any observed differences between DPOAE levels in different suppressor conditions could not be attributed to differences in the noise floor between conditions, the noise levels were analyzed using a repeated measures design with three within-subject factors: suppressor condition (four levels), f2 frequency (two levels), and run (five levels). Tests of within-subjects effects showed no significant main effects of f2 frequency [$F(1,6) = 4.538$, $p > .05$], suppressor condition [$F(3,18) = 2.521$, $p > .05$], or run [$F(4,24) = 1.267$, $p > .05$] on the noise levels, and there were no significant interactions [f2 frequency by suppressor condition: $F(3,18) = 3.386$, $p > .05$; f2 frequency by run: $F(4, 24) = .073$, $p > .05$; suppressor condition by run: $F(12, 72) = 1.360$, $p > .05$; f2 frequency by suppressor condition by run: $F(12, 72) =$

0.972, $p > .05$]. Therefore, any significant effects of suppressor condition cannot be attributed to systematic differences in the noise floors between conditions.

Because there were no significant main effects or interactions related to the f2 frequency, further analyses were conducted on the data for each f2 frequency condition separately in order to use all available data.

DPOAE and noise levels for f2 = 2000 Hz. Analyses were conducted to investigate the effect of suppression condition and run on DPOAE levels and noise levels. Mean DPOAE and noise levels in the four conditions and five runs obtained from the 10 participants at the f2 = 2000 Hz frequency are shown in Figure 6. Mean data for the four suppressor conditions are shown separately for each of the five runs (panels a – e) and averaged across all five runs (panel f). A repeated measures ANOVA was conducted with two within-subjects factors: suppressor condition (four levels – no suppressor, narrowest BW suppressor, ERB BW suppressor, widest BW suppressor) and run (five levels – five runs). Tests of within-subjects effects showed significant main effects of suppressor condition [$F(3,27) = 6.081$, $p < .01$], and run [$F(4, 36) = 3.501$, $p < .05$]. There was no significant interaction between suppressor condition and run [$F(12,108) = 0.720$, $p > .05$].

Mean DPOAE levels for the four suppressor conditions averaged across the five runs are shown in Figure 6 (panel f) and are re-drawn as a bar graph (Figure 7) for easier viewing of the DPOAE levels. Helmert planned contrasts were used to investigate the source of the main effect of significance within the suppressor condition according to the hypotheses of Experiment 1. A Helmert planned contrast compares a level (in this case, suppressor condition) to the mean effect of all

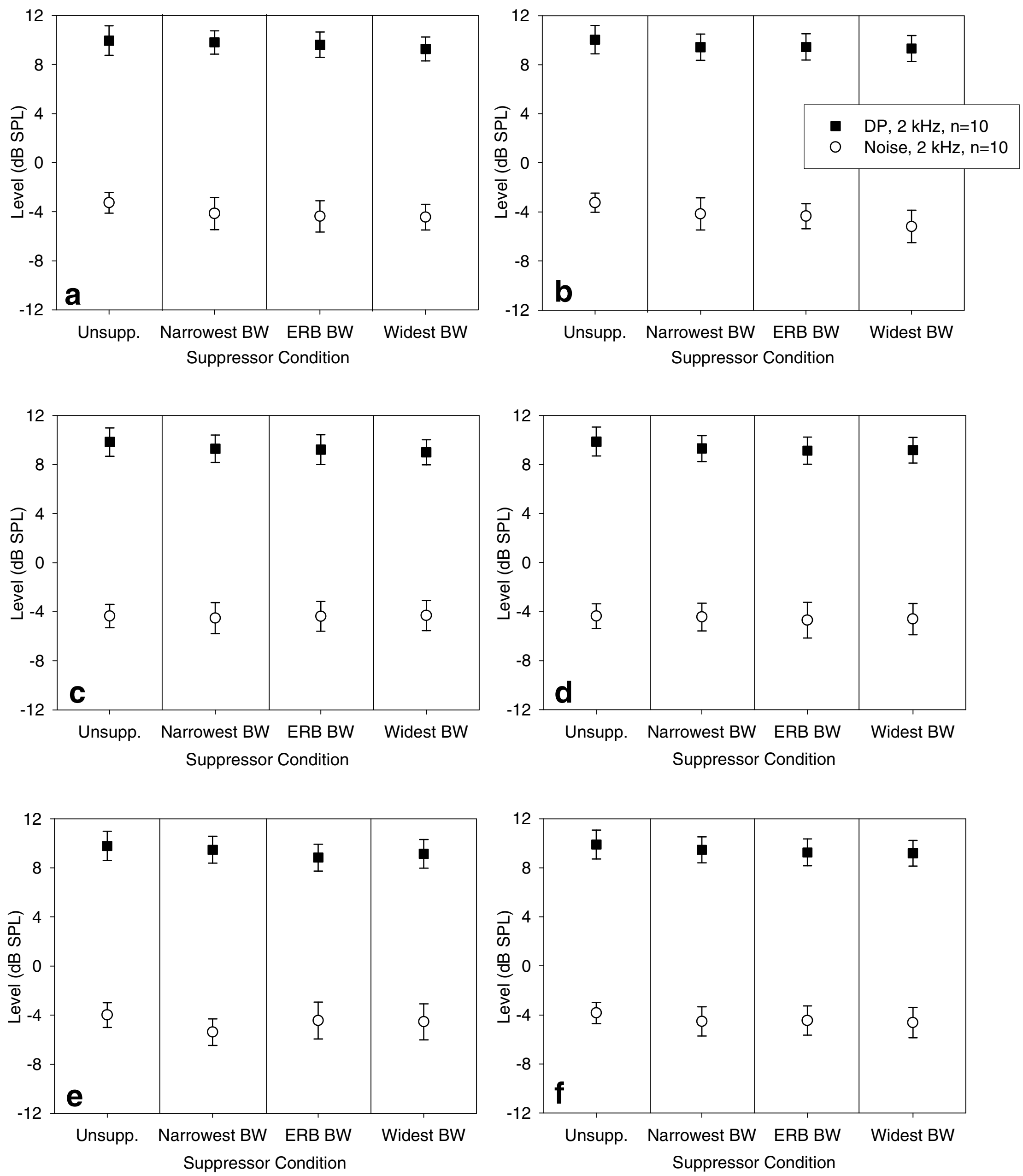

Figure 6. Mean DPOAE levels and noise levels are shown for the 10 participants who provided usable data for f2 = 2000 Hz in Experiment 1. Mean levels for the four suppressor conditions are shown separately for each of the five runs included in analysis (panels a – e) and averaged across the five runs (panel f). Error bars represent one standard error of the mean.

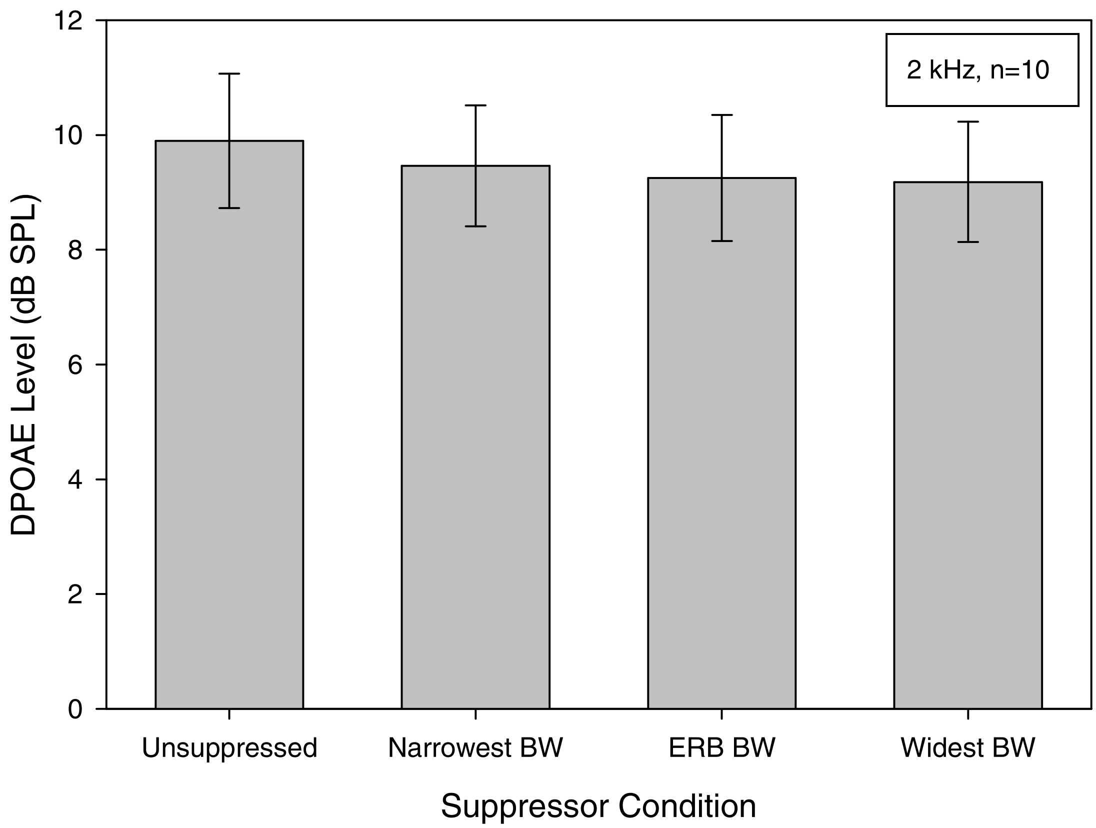

Figure 7. Mean DPOAE levels in each suppressor condition, averaged across the five runs, for Experiment 1, f2 = 2000 Hz. Error bars represent one standard error of the mean.

subsequent levels. To analyze the data in Experiment 1, the Helmert contrast first compared the unsuppressed condition to the mean effect of all subsequent three suppressor BW conditions. Then, the narrowest BW was compared to the mean of the combined ERB and widest BW suppressors. Finally, the ERB BW suppressor was compared to the widest BW suppressor (see Figure 8). These contrasts revealed that the mean DPOAE level in the unsuppressed condition was significantly higher than the mean effect of all of the subsequent suppressed conditions [$F(1,9) = 8.556$, $p < .05$], but they showed no significant differences in DPOAE level between the narrowest BW condition and the mean of the ERB BW and widest BW conditions [$F(1,9) = 2.759$, $p > .05$], or between the ERB BW and widest BW conditions [$F(1,9) = .447$, $p > .05$].

Figure 9 shows the individual participants' DPOAE levels across the five runs, averaged across the four suppressor conditions. Data were averaged across the four suppressor conditions because the main effect of run was not involved in a significant interaction with condition. While there is some variability in overall DPOAE levels evident between individual participants, each participant provides reasonably stable DPOAE levels and noise levels across the five runs. Paired sample t-tests with Bonferroni correction were used for post hoc investigation of the source of the significant run effect. There were no significant differences identified between each pair of runs, $p > .05$. The absence of significant differences in this post hoc analysis, in the presence of a main effect of run, may be due to the different error terms used in the main effects and post hoc analyses. The post hoc comparisons show no differences between any of the runs, and visual inspection of the individual data

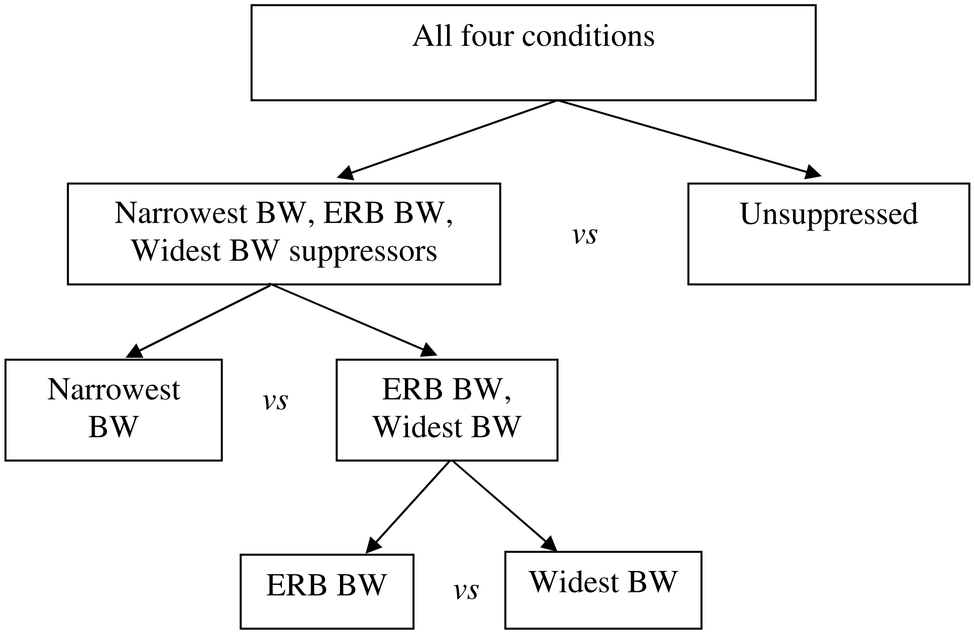

Figure 8. Schematic diagram of sequence of Helmert planned contrasts used for Experiment 1.

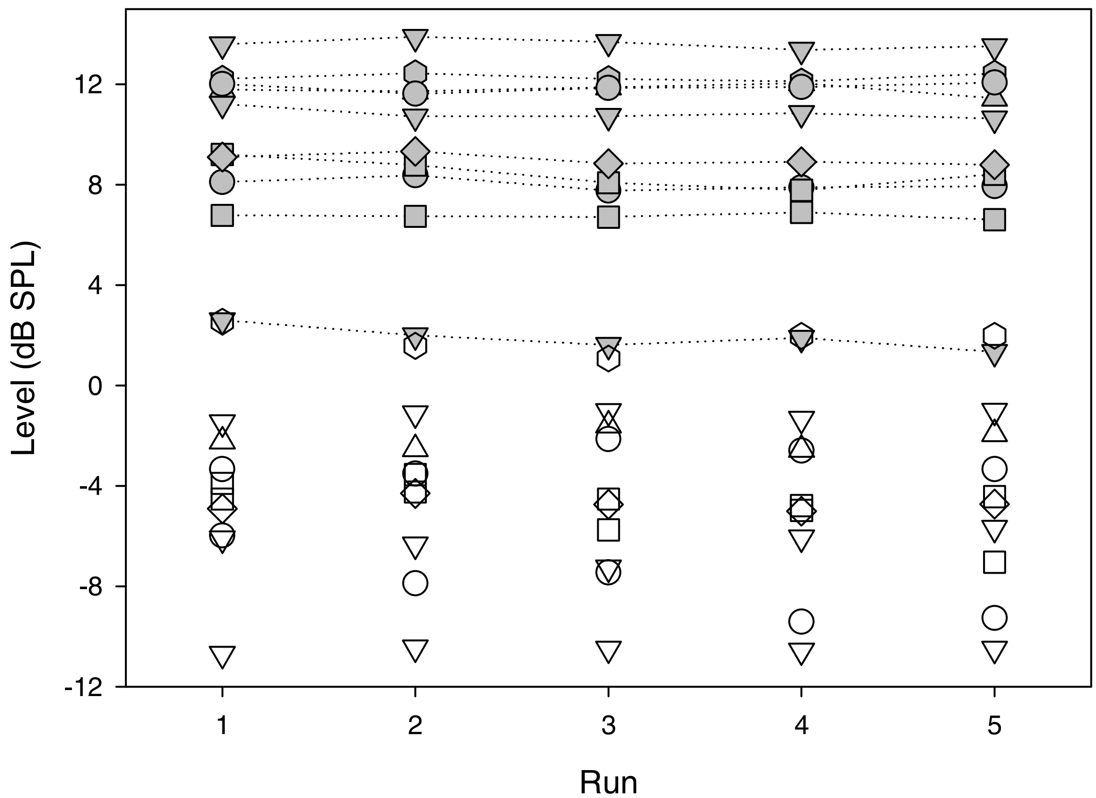

Figure 9. DPOAE and noise levels for the five runs for each participant in Experiment 1, f2 = 2000 Hz, averaged across the four suppressor conditions. Shaded symbols show DPOAE levels; open symbols show noise levels. DPOAE levels from the same participant are connected with a line.

across the five runs shows no apparent trends (see Figure 5). Therefore, it is likely that the effect of run was inflated in the main analysis.

In addition to the analyses of DPOAE levels, an analysis of noise levels was conducted to determine whether or not there were significant effects of suppressor condition and run on the noise levels. Results of a repeated measures ANOVA (the two within-subjects variables were suppressor condition and run) revealed no significant effect of suppressor condition [$F(1.404, 12.638) = 1.860$, $p > .05$ (Greenhouse-Geisser)], no significant effect of run [$F(4, 36) = .858$, $p > .05$], and no significant interaction of suppressor condition by run [$F(3.363, 30.271) = 1.043$, $p > .05$ (Greenhouse-Geisser)]. Figure 6 provides an illustration of the noise levels for each suppressor condition in each of the five runs (panels a – e) and for the noise data averaged across all five runs (panel f).

DPOAE and noise levels for f2 = 4000 Hz. The effect of suppressor condition and run on DPOAE and noise levels was investigated for all usable data for f2 = 4000 Hz. Mean DPOAE levels in the four conditions are shown separately for each of the five runs in Figure 10 (panels a – e) as well as averaged across the five runs (panel f). A repeated measures ANOVA was used with two within-subjects factors: suppressor condition (four levels) and run (five levels). Tests of within-subjects effects showed a significant main effect of suppressor condition [$F(1.681, 16.808) = 5.883$, $p < .05$ (Greenhouse-Geisser)], but there was no significant main effect of run [$F(1.613, 16.133) = 3.846$, $p > .05$ (Greenhouse-Geisser)] and no significant interaction between suppressor condition and run [$F(4.126, 41.259) = .705$, $p > .05$ (Greenhouse-Geisser)].

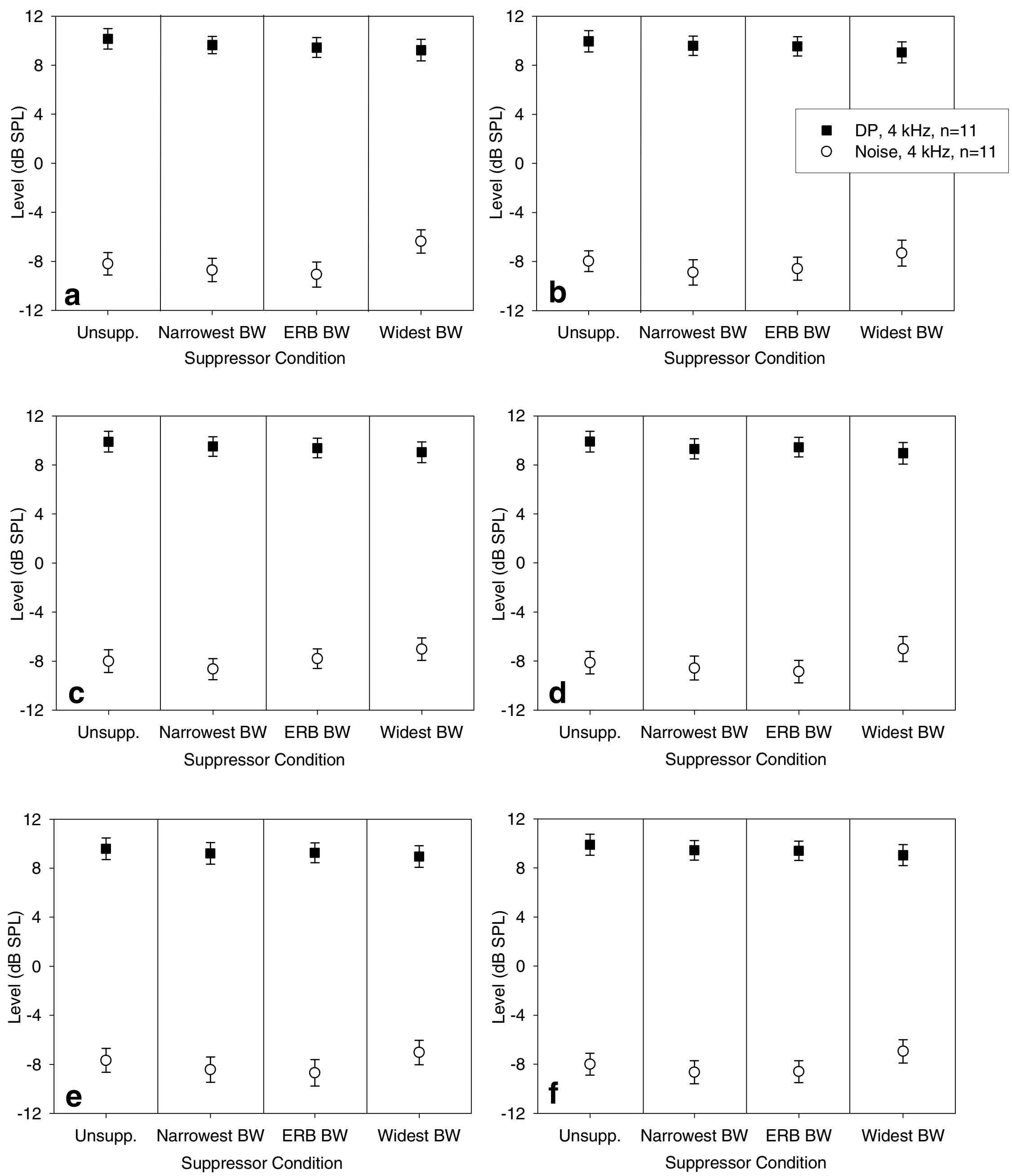

Figure 10. Mean DPOAE levels and noise levels are shown for the 11 participants who provided usable data for f2 = 4000 Hz in Experiment 1. Mean levels for the four suppressor conditions are shown separately for each of the five runs included in analysis (panels a – e) and averaged across the five runs (panel f). Error bars represent one standard error of the mean.

Mean DPOAE level was collapsed across run for each of the four suppressor conditions, because the run effect was not involved in any interactions. These mean DPOAE levels are shown in Figure 10 (panel f) and are re-drawn as a bar graph for easier viewing of the DPOAE levels only in Figure 11. Helmert planned contrasts were used to investigate the source of the main effect of significance within the suppressor condition according to the hypotheses, using the same contrasts illustrated in the previous section for f2 = 2000 Hz (see Figure 8). These contrasts revealed a significant difference between the mean level of the unsuppressed condition and the mean effect of all the subsequent suppressed conditions [$F(1,10) = 10.626$, $p < .01$], but they showed no significant differences between the narrowest BW condition and the mean of the ERB BW and widest BW conditions [$F(1,10) = 3.172$, $p > .05$], or between the ERB BW and widest BW conditions [$F(1,10) = 2.371$, $p > .05$].

To determine whether there was an effect of suppressor condition on the noise levels (see Figure 10), a repeated measures ANOVA was used with two within-subjects factors: suppressor condition and run. Results showed no significant effect of suppressor condition [F (1.305, 13.050) = 2.350, $p > .05$ (Greenhouse-Geisser)], no significant effect of run [F (4, 40) = .235, $p > .05$], and no significant interaction of suppressor condition by run [F (4.114, 41.144) = 2.092, $p > .05$ (Greenhouse-Geisser)].

Magnitude of suppression. In order to facilitate comparison of these data with those reported by others, the magnitude of DPOAE suppression was derived and analyzed. Magnitude of suppression was calculated by subtracting the mean of each participant's DPOAE levels in each suppressor (narrowband noise masker) condition

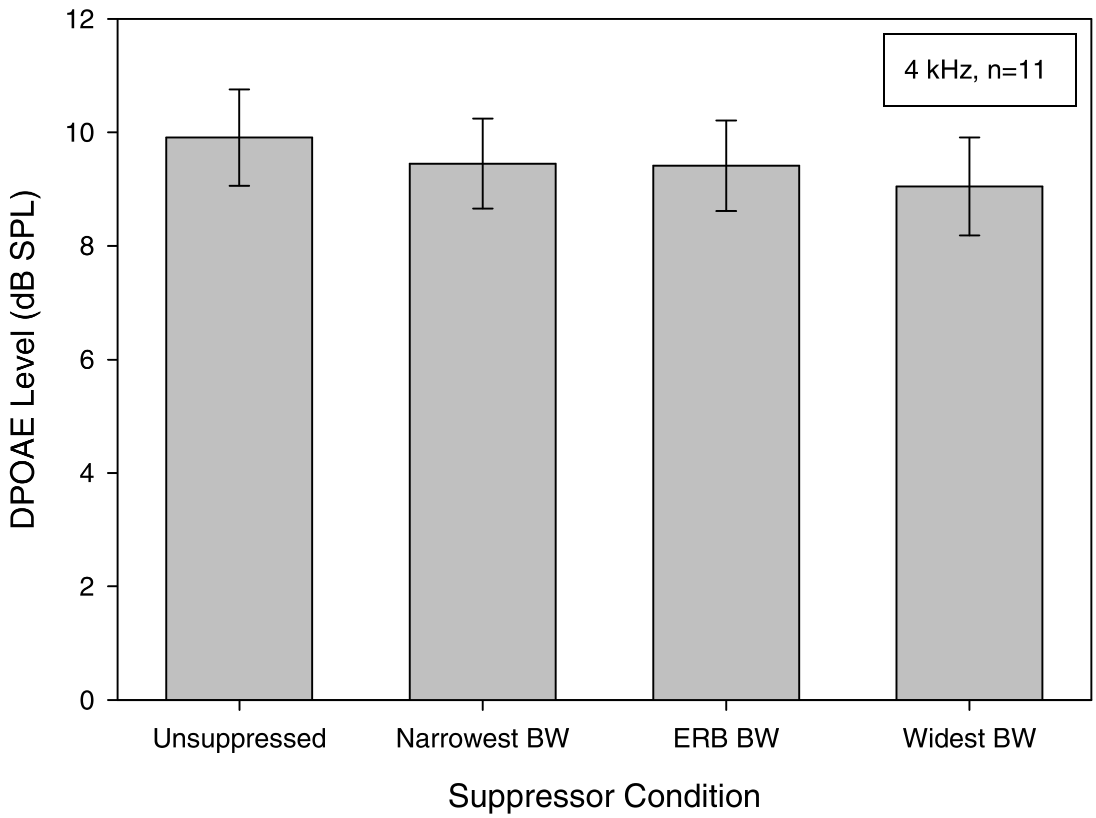

Figure 11. Mean DPOAE levels in each suppressor condition, averaged across the five runs, for Experiment 1, f2 = 4000 Hz. Error bars represent one standard error of the mean.

from the mean of her unsuppressed DPOAE levels. Therefore, there were three levels of the suppressor condition factor in the analysis rather than the four used in the analyses of DPOAE level. Additionally, run was not a factor in these analyses, because DPOAE levels from the five runs in each condition were averaged. Figure 12 shows the magnitudes of suppression from the subset of seven participants who provided usable data for both f2 = 2000 Hz and f2 = 4000 Hz. Although the magnitude of suppression appears to increase with increasing bandwidth, a repeated measures analysis of variance revealed no significant main effects of f2 frequency [$F(1,6)=0.000$, $p > .05$] and suppressor condition [$F(1.266, 7.597) = 4.383$, $p > .05$ (Greenhouse-Geisser)] and no interaction between these factors [$F(1.115, 6.689) = 1.992$, $p > .05$ (Greenhouse-Geisser)].

As with the analyses of DPOAE level, this analysis of the magnitudes of suppression was also conducted separately for f2 = 2000 Hz and f2 = 4000 Hz to include all available data in each f2 frequency condition. The same repeated measures design was used, with just one factor: suppressor condition (three levels). No main effect of suppressor condition was found for f2 = 2000 Hz [$F(2,18)=2.153$, $p > .05$] or f2 = 4000 Hz [$F(1.060,10.596)=2.586$ (Greenhouse-Geisser), $p > .05$]. The magnitudes of suppression for each f2 frequency are shown in Figure 13; data for f2 = 2000 Hz are shown in panel (a), and data for f2 = 4000 Hz are shown in panel (b).

Effect of SOAEs. Nine participants who provided usable data in Experiment 1 had present SOAEs, and four did not. SOAE data were not collected in one participant (see Table 2). For those participants with data for f2 = 2000 Hz, seven

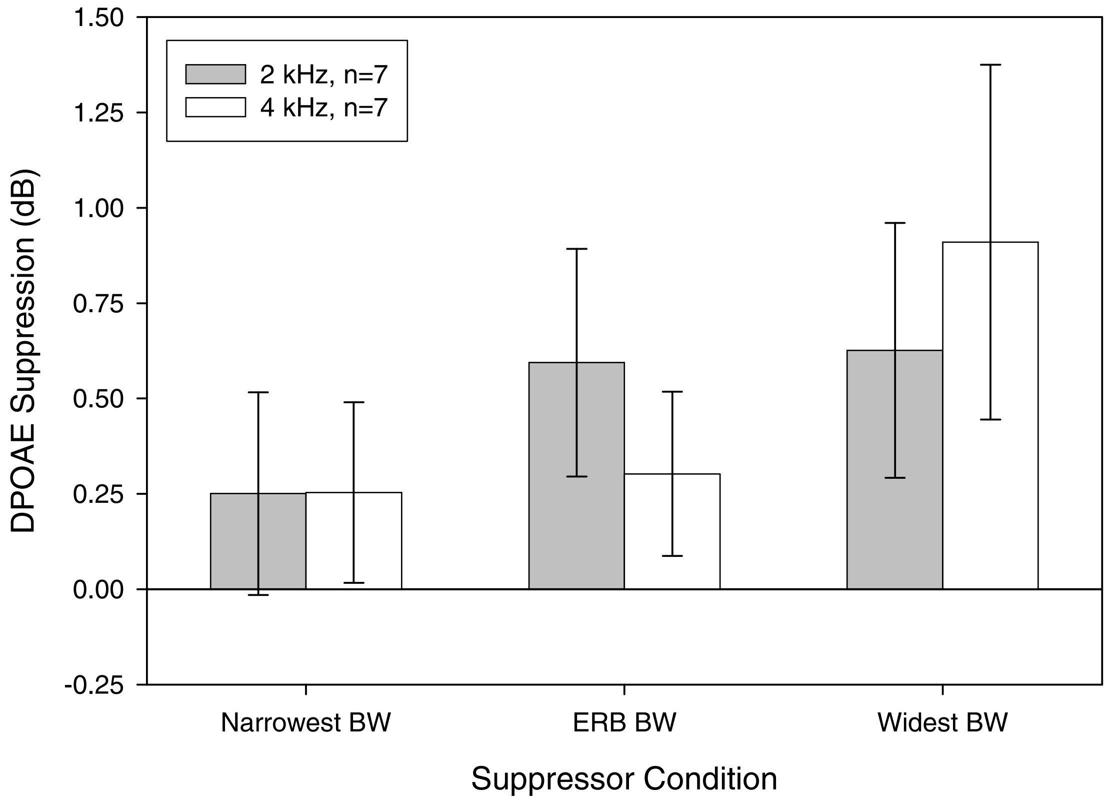

Figure 12. Mean magnitude of DPOAE suppression is shown for each suppressor condition for the subset of seven participants who provided usable data for both f2 = 2000 Hz and f2 = 4000 Hz in Experiment 1. Error bars represent one standard error of the mean.

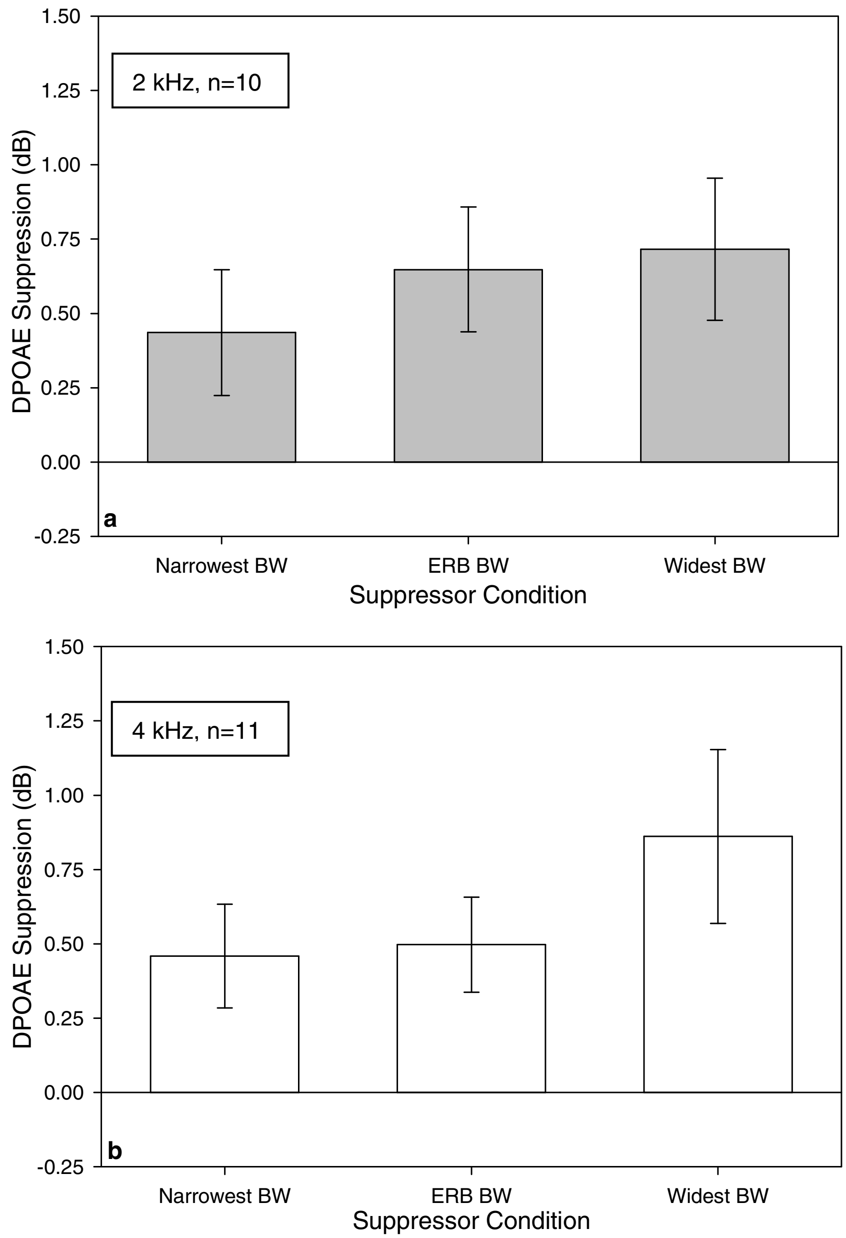

Figure 13. Panel (a) shows mean magnitude of DPOAE suppression achieved by each suppressor BW for f2 = 2000 Hz, and panel (b) shows mean magnitude of suppression achieved by each suppressor BW for f2 = 4000 Hz for all participants who provided usable data in Experiment 1. Error bars represent one standard error of the mean.

had SOAEs and three did not. For those who participated in f2 = 4000 Hz, seven had SOAEs and three did not. In order to determine whether the presence or absence of SOAEs had a significant effect on the observed effect of suppressor condition on DPOAE level, a repeated measures design was used, with SOAE as a between-subjects factor with two levels (present SOAEs, absent SOAEs), and suppressor condition (four levels) and run (five levels) as within-subjects factors. Because there were only two participants with absent SOAEs who had data for both f2 frequencies, an analysis of the effect of SOAE group for both f2 frequencies was not conducted. Figure 14 shows the data obtained from the two groups for f2 = 2000 Hz (panel a) and f2 = 4000 Hz (panel b).

Results of data analysis for f2 = 2000 Hz show a significant effect of presence/absence of SOAEs; participants with SOAEs had significantly larger DPOAE levels [$F(1, 8) = 8.455$, $p < .05$]. However, there were no significant interactions between SOAE and suppressor condition [$F(3, 24) = 1.482$, $p > .05$], between SOAE and run [$F(4, 32) = .741$, $p > .05$], and between SOAE, suppressor condition, and run [$F(12, 96) = 1.678$, $p > .05$]. Results of main effects analysis of suppressor condition and run have been reported in previous sections for the entire dataset and those results are not repeated here.

Similar results are found for the f2 = 4000 Hz condition. Participants with SOAEs had significantly larger DPOAE levels, [$F(1, 8) = 6.863$, $p < .05$]. However, there were no significant interactions between SOAE and suppressor condition [$F(1.555, 12.438) = .463$, $p > .05$ (Greenhouse-Geisser)], between SOAE and run

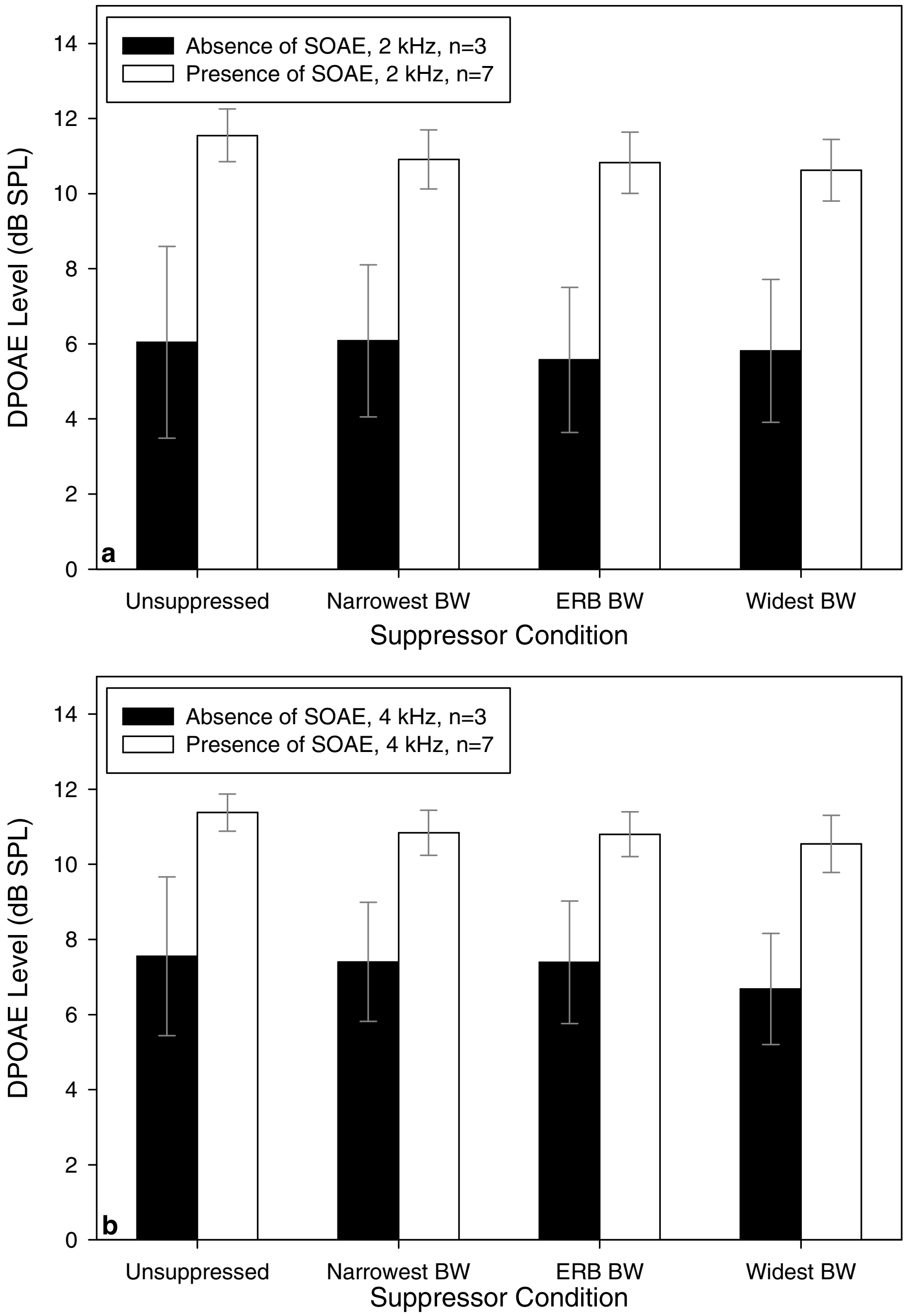

Figure 14. Mean DPOAE levels for the two SOAE groups in each of the four suppressor conditions in Experiment 1. Panel (a) shows the data for f2 = 2000 Hz, and panel (b) shows data for f2 = 4000 Hz. Error bars represent one standard error of the mean.

[F(1.599, 12.790) = 1.433, $p > .05$ (Greenhouse-Geisser)], and between SOAE, suppressor condition, and run [F(3.269, 26.153) = 1.402, $p > .05$].

Figure 15 shows these same data re-plotted as magnitude of suppression; data for f2 = 2000 Hz are shown in panel (a), and data for f2 = 4000 Hz are shown in panel (b). The effect of SOAE group was analyzed using the same repeated measures design but with three levels of the suppressor condition and no run factor. This analysis eliminates the influence of overall DPOAE level for each individual on the comparison between groups and instead looks only at differences in the effect of the suppressor between SOAE groups. For f2 = 2000 Hz, no significant main effect of SOAE was found [F(1,8) = 1.564, $p > .05$], and there was no interaction between SOAE and suppressor condition [F(2, 16) = 1.356, $p > .05$]. For f2 = 4000 Hz, no significant main effect of SOAE was found [F(1, 8) = .313, $p > .05$], and there was no interaction between SOAE and suppressor condition [F(1.061, 8.490) = .566, $p > .05$ (Greenhouse-Geisser)].

In general, while these results do not support the hypothesis regarding the effect of bandwidth, they do demonstrate that significant DPOAE suppression can be measured using noise suppressors presented in a forward masking paradigm. The f2 frequency had no significant effect on the results. While a statistically significant effect of run was found for the f2 = 2000 Hz data, this effect is not evident upon visual inspection of the data, and its significance is not borne out in post hoc analysis. A statistically significant difference in DPOAE amplitudes was found between the groups of participants with and without SOAEs, but no difference between groups was found for the comparison of magnitudes of suppression.

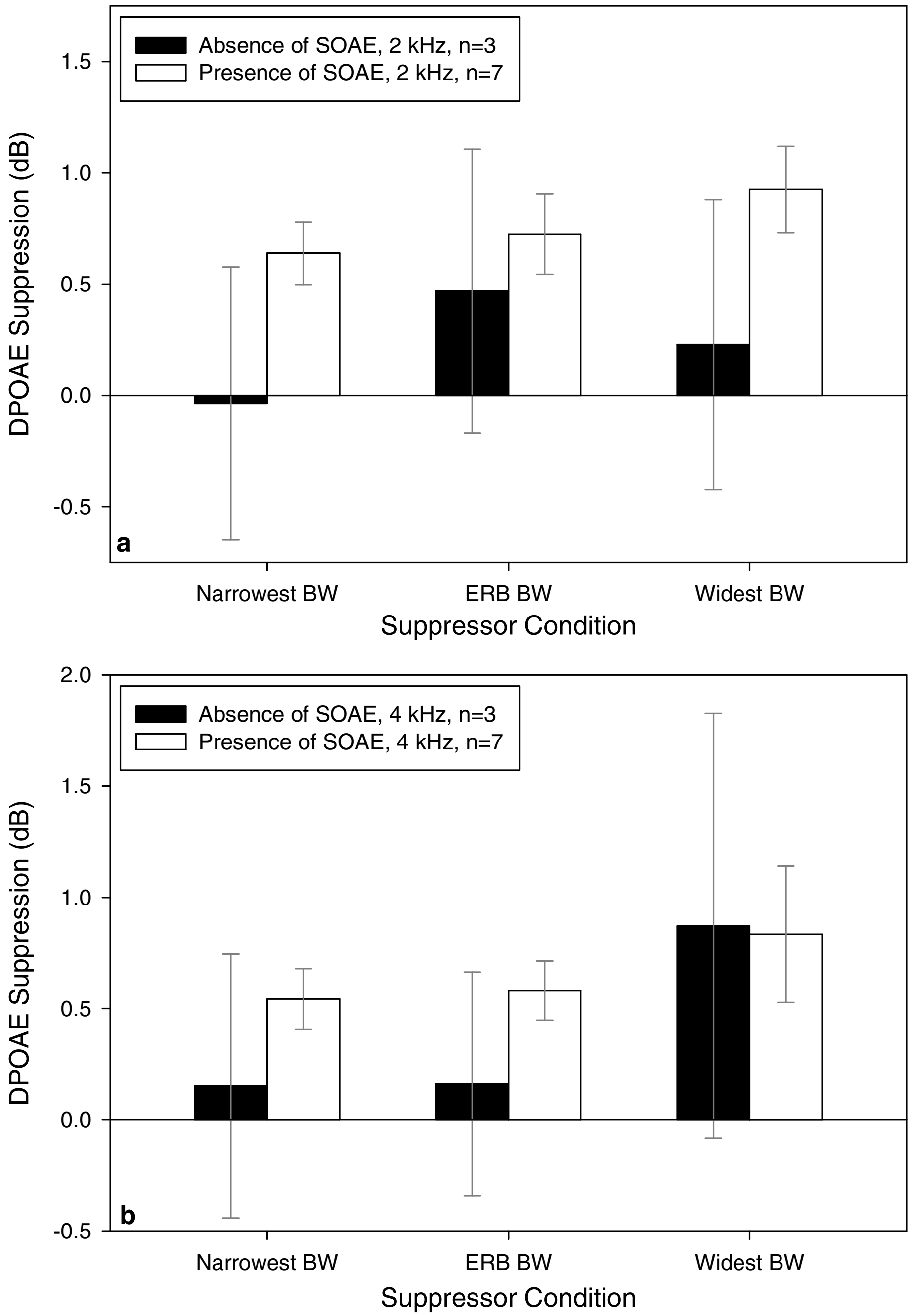

Figure 15. Mean magnitude of DPOAE suppression shown for each of the three suppressed conditions for the two SOAE groups in Experiment 1. Panel (a) shows the data for f2 = 2000 Hz, and panel (b) shows data for f2 = 4000 Hz. Error bars represent one standard error of the mean.

Experiment 2

This experiment was designed to investigate whether the center frequency of narrowband noise suppressors affects DPOAE suppression in an ipsilateral forward masking paradigm. DPOAE levels and noise levels obtained from participants were analyzed to determine the effect of f2 frequency, suppressor condition (no suppressor, and three suppressors varying in noise center frequency), and run.

Effect of f2 frequency. The mean DPOAE levels and noise levels of the seven participants who provided usable data for both f2 frequencies are shown in Figure 16. Means for each of the four suppressor conditions are shown for each run (panels a – e) and averaged across runs (panel f). As in Experiment 1, the effect of f2 frequency was analyzed for a subset of participants, because usable data for both f2 frequencies could not be obtained from all participants in Experiment 2. To determine whether there was an effect of the f2 frequency on the DPOAE level measured for the different suppressor conditions, the subset of data from the seven participants who took part in both f2 frequency conditions was analyzed using a repeated measures design with three within-subject factors: suppressor condition (four levels – no suppressor, suppressor centered below f2, suppressor centered at f2, and suppressor centered above f2), f2 frequency (two levels - 2000 Hz and 4000 Hz), and run (five levels - five runs per condition). The main effects and interactions of these factors were compared using a Bonferroni confidence interval adjustment. Tests of within-subjects effects showed no significant main effect of f2 frequency [$F(1,6) = 2.223$, $p > .05$] a significant main effect of suppressor condition [$F(3,18) = 5.683$, $p < .01$], and no significant main effect of run [$F(1.496,8.974) = .621$ $p > .05$ (Greenhouse-

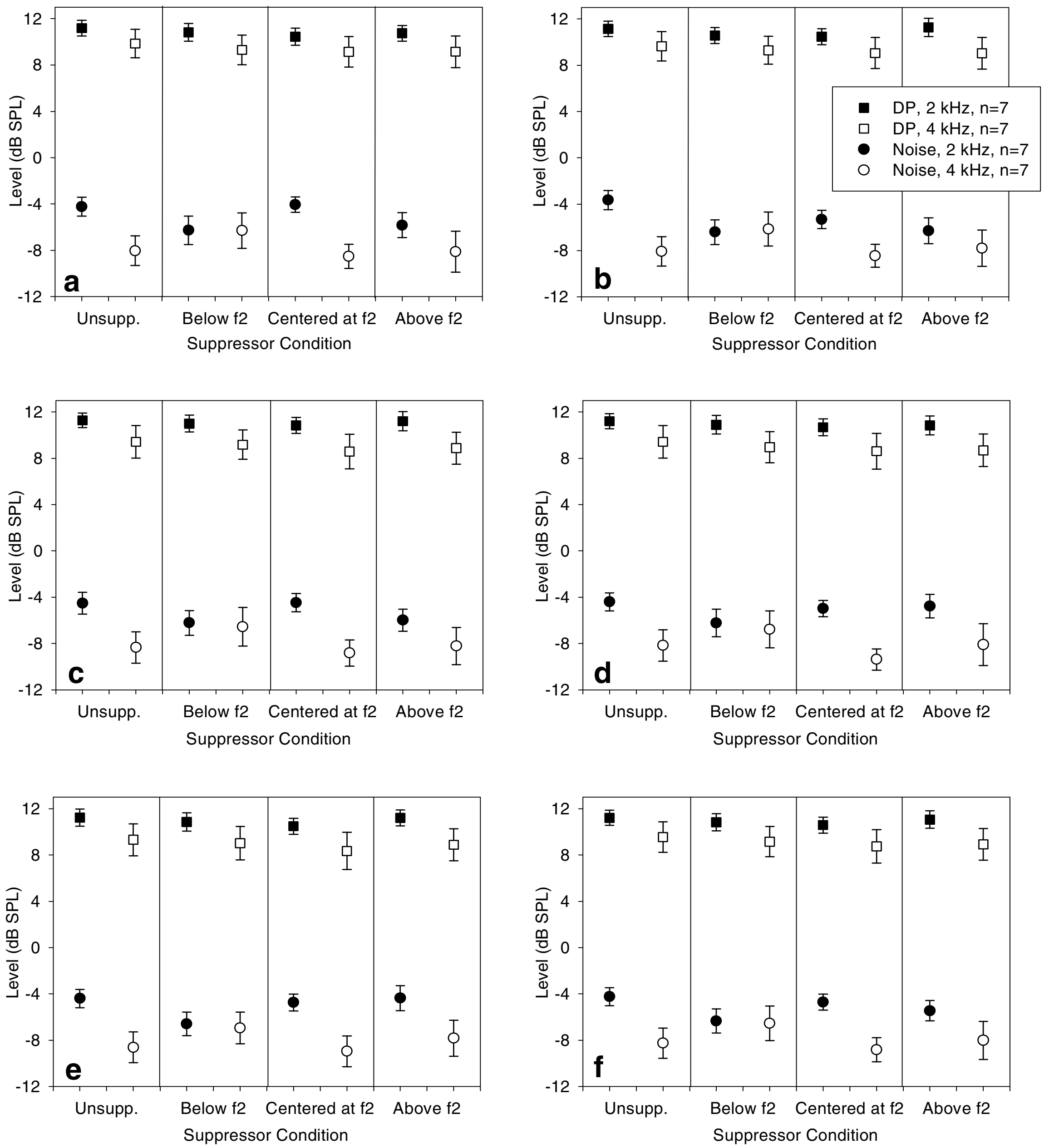

Figure 16. Mean DPOAE levels and noise levels are shown for the subset of seven participants who provided usable data for both f2 = 2000 Hz (filled symbols) and f2 = 4000 Hz (open symbols) in Experiment 2. Mean levels are shown for the four suppressor conditions in each of five runs used in analysis (panels a – e) and averaged across the five runs (panel f). Error bars represent one standard error of the mean.

Geisser)]. There were no significant interactions between these factors [f2 frequency by run: $F(1.321, 7.928) = 1.401$, $p > .05$ (Greenhouse Geisser); suppressor condition by run: $F(3.863, 23.179) = .763$, $p > .05$ (Greenhouse-Geisser); f2 frequency by suppressor condition by run: $F(3.322, 19.931) = .981$, $p > .05$ (Greenhouse-Geisser)].

To ensure that any observed differences between suppressor conditions could not be attributed to differences in the noise floor between conditions, the noise levels were analyzed using a repeated measures design with three within-subject factors: suppressor condition (four levels), f2 frequency (two levels), and run (five levels). Tests of within-subjects effects showed no significant main effects of f2 frequency [$F(1,6) = 1.188$, $p > .05$], suppressor condition [$F(1.483, 8.897) = .951$, $p > .05$ (Greenhouse-Geisser)], or run [$F(4,24) = .136$, $p > .05$] on the noise levels, and there were no significant interactions [f2 frequency by suppressor condition: $F(3, 18) = 3.079$, $p > .05$; f2 frequency by run: $F(1.788, 10.726) = .683$, $p > .05$ (Greenhouse-Geisser); suppressor condition by run: $F(3.860, 23.158) = 1.253$, $p > .05$ Greenhouse-Geisser); f2 frequency by suppressor condition by run: $F(3.270, 19.619) = .535$, $p > .05$ (Greenhouse-Geisser)]. Therefore, it is unlikely that any significant effects of suppressor condition on DPOAE levels are related systematically to behavior of the noise levels between conditions.

DPOAE and noise levels for f2 = 2000 Hz. Analyses were conducted to investigate the effect of suppression condition and run on DPOAE levels and noise levels for each f2 frequency separately. Mean data in the four conditions for f2 = 2000 Hz are shown separately for each of the five runs in Figure 17 (panels a – e) and

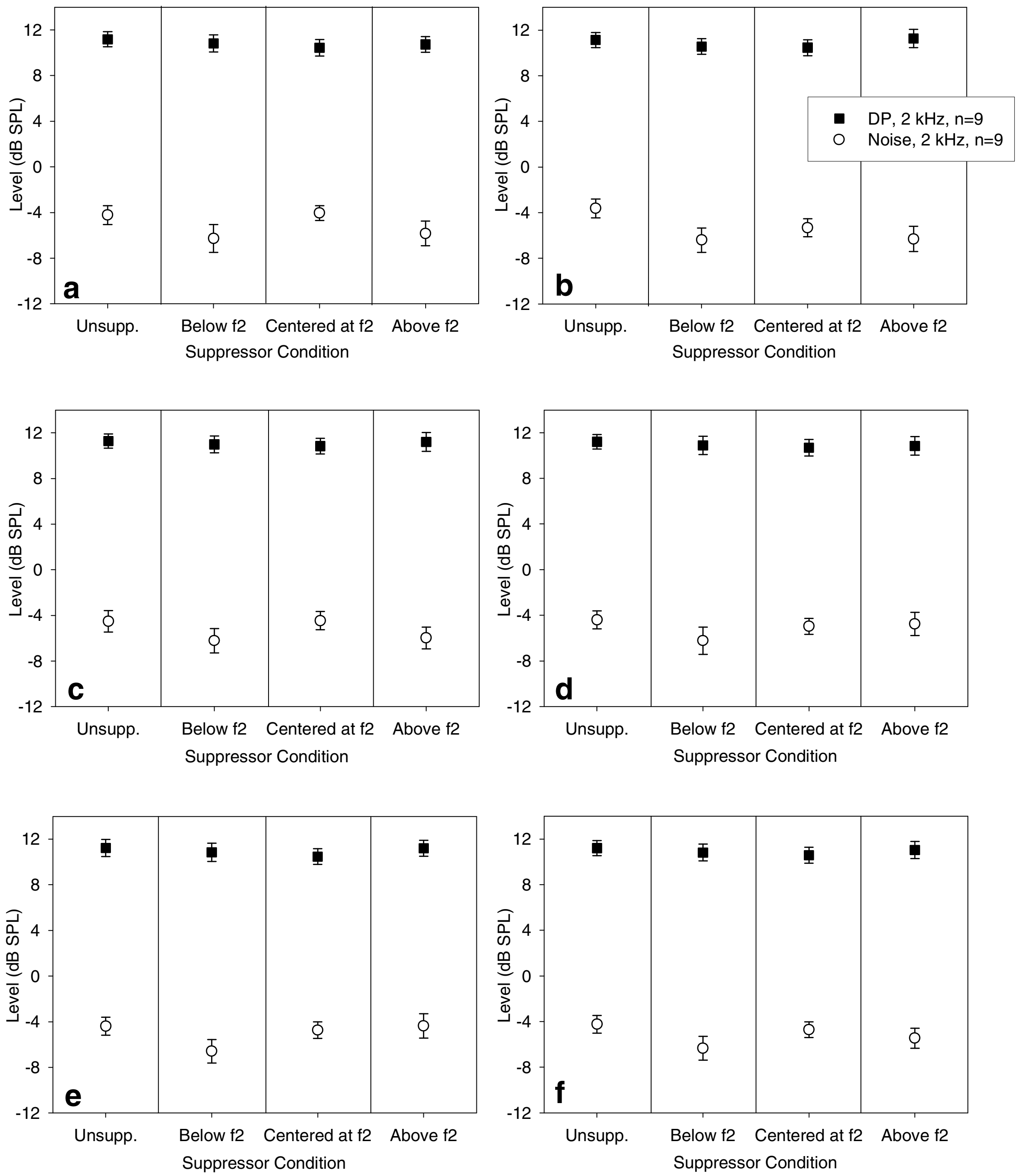

Figure 17. Mean DPOAE levels and noise levels are shown for all nine participants who provided usable data for f2 = 2000 Hz in Experiment 2. Mean levels for the four suppressor conditions are shown separately for each of the five runs included in analysis (panels a – e) and averaged across all five runs (panel f). Error bars represent one standard error of the mean.

averaged across all runs (panel f). Data were analyzed using a repeated measures ANOVA with two within-subject factors: suppressor condition (four levels) and run (five levels). Tests of within-subjects effects showed a significant main effect of suppressor condition [$F(1.397,11.176) = 4.555$, $p < .05$ (Greenhouse-Geisser)]. There was no significant main effect of run [$F(2.338, 18.707) = .989$, $p > .05$ (Greenhouse-Geisser)], and there was no significant interaction between suppressor condition and run [$F(4.338, 34.705) = .850$, $p > .05$ (Greenhouse-Geisser)].

Panel (f) of Figure 17 shows the mean DPOAE level across the four suppressor conditions collapsed across run, and these data are re-drawn as a bar graph for easier viewing of the DPOAE levels in Figure 18. Helmert planned contrasts were used to investigate the source of the main effect of significance within the suppressor condition according to the hypothesis regarding the effect of suppressor center frequency (see Figure 19). To test this hypothesis, the Helmert contrast first compared the condition with suppressor centered at the f2 frequency to the mean effect of the subsequent other three conditions. Then the unsuppressed condition was compared to the mean effect of the combined conditions with suppressor centered below and above the f2 frequency. Finally, the condition with suppressor centered below the f2 frequency was compared to the condition with suppressor centered above the f2 frequency. Helmert contrasts revealed that the suppressor centered on the f2 frequency yielded lower DPOAE levels compared to the mean effect of the other three conditions [$F(1,8) = 14.790$, $p < .01$]. There was no significant difference between the unsuppressed condition and the mean effect of the combined conditions where the suppressor was centered above and below the f2 frequency [$F(1,8) = 1.419$,

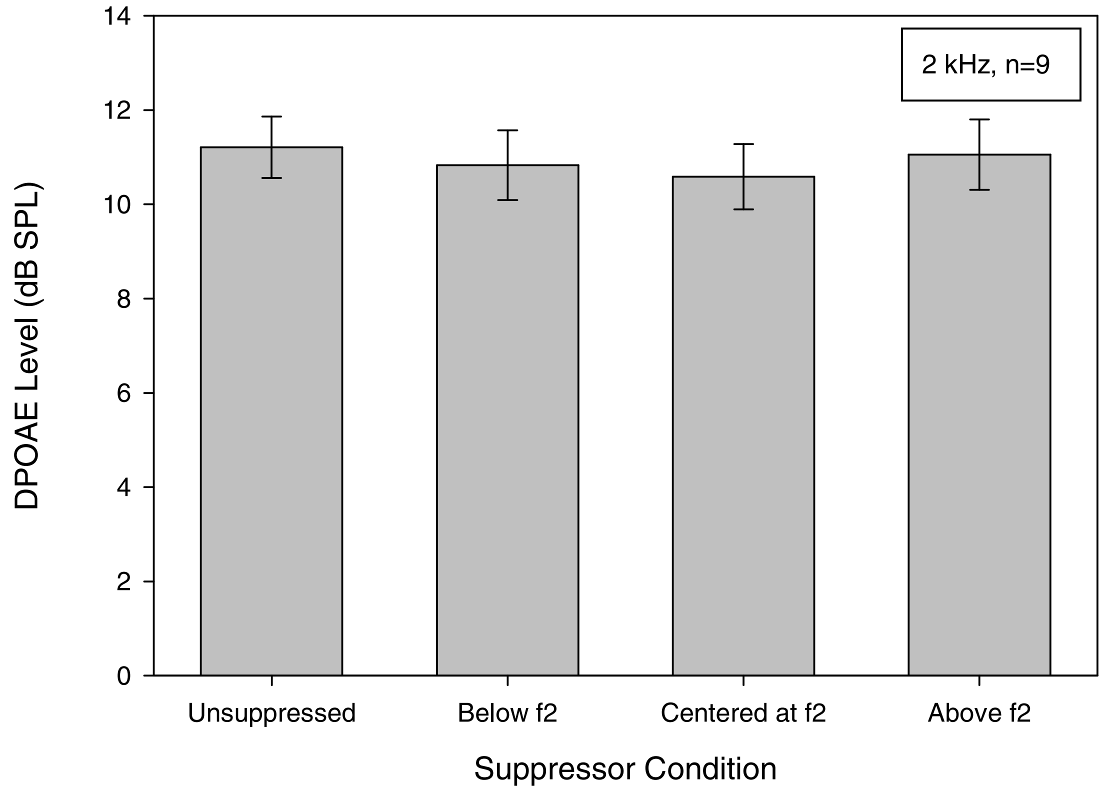

Figure 18. Mean DPOAE levels of nine participants in each suppressor condition, averaged across the five runs, for Experiment 2, f2 = 2000 Hz. Error bars represent one standard error of the mean.

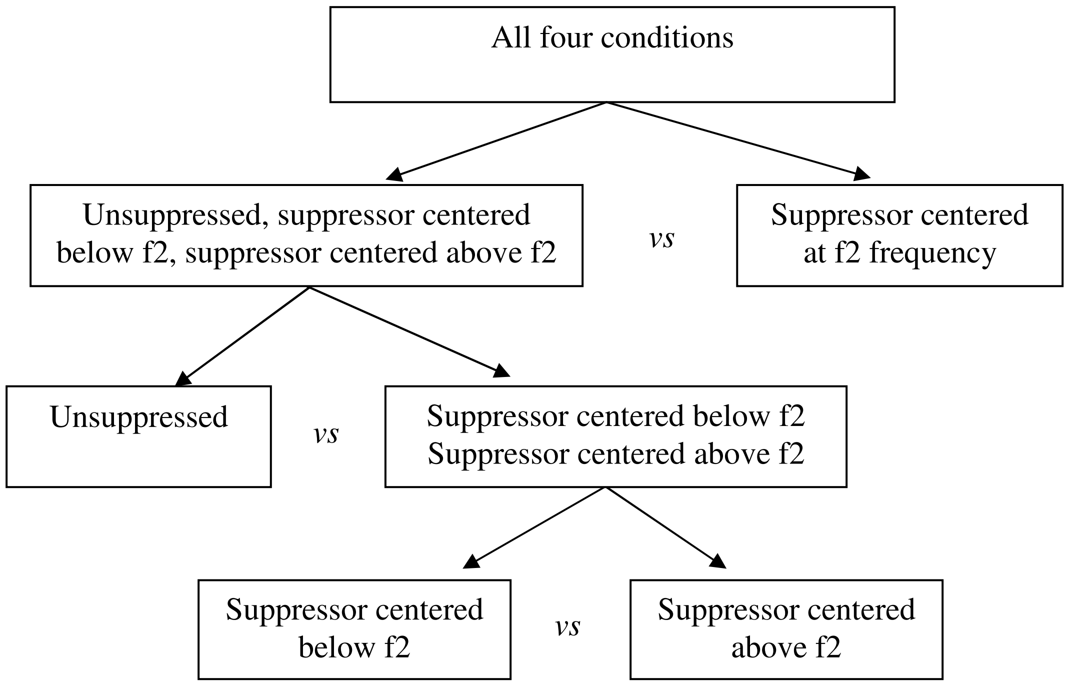

Figure 19. Schematic diagram of sequence of Helmert planned contrasts used for Experiment 2.

$p > .05$]. There was a significant difference in DPOAE levels when the suppressor was centered above the f2 frequency and when the suppressor was centered below the f2 frequency [$F(1,8) = 5.483$, $p < .05$], with the lower frequency suppressor yielding lower DPOAE levels than the higher frequency suppressor.

To determine whether there was an effect of suppressor condition on the noise levels (see Figure 17), data were analyzed using a repeated measures ANOVA with two within-subject factors: suppressor condition (four levels) and run (five levels). Results showed no significant effect of suppressor condition [$F(3, 24) = 1.518$, $p > .05$], no significant effect of run [$F(4, 32) = 1.658$, $p > .05$], and no significant interaction [$F(12, 96) = .568$, $p > .05$].

DPOAE and noise levels for f2 = 4000 Hz. The effect of suppressor condition and run on DPOAE levels and noise levels was investigated when f2 = 4000 Hz. Mean data in the four conditions and five runs obtained from the nine participants at the f2 = 4000 Hz frequency are shown in Figure 20. Mean data in each condition are shown separately for each run (panels a – e) and averaged across runs (panel f). Data were analyzed using a repeated measures ANOVA with two within-subject factors: suppressor condition (four levels) and run (five levels). Tests of within-subjects effects showed no main effect of suppressor condition [$F(3,24) = 1.967$, $p > .05$], or run [$F(1.154, 9.229) = 2.220$, $p > .05$], and there was no interaction between suppressor condition and run [$F(2.706, 21.652) = .614$, $p > .05$].

To determine whether there was an effect of suppressor condition on the noise levels in the DPOAE recordings, data were analyzed using a repeated measures

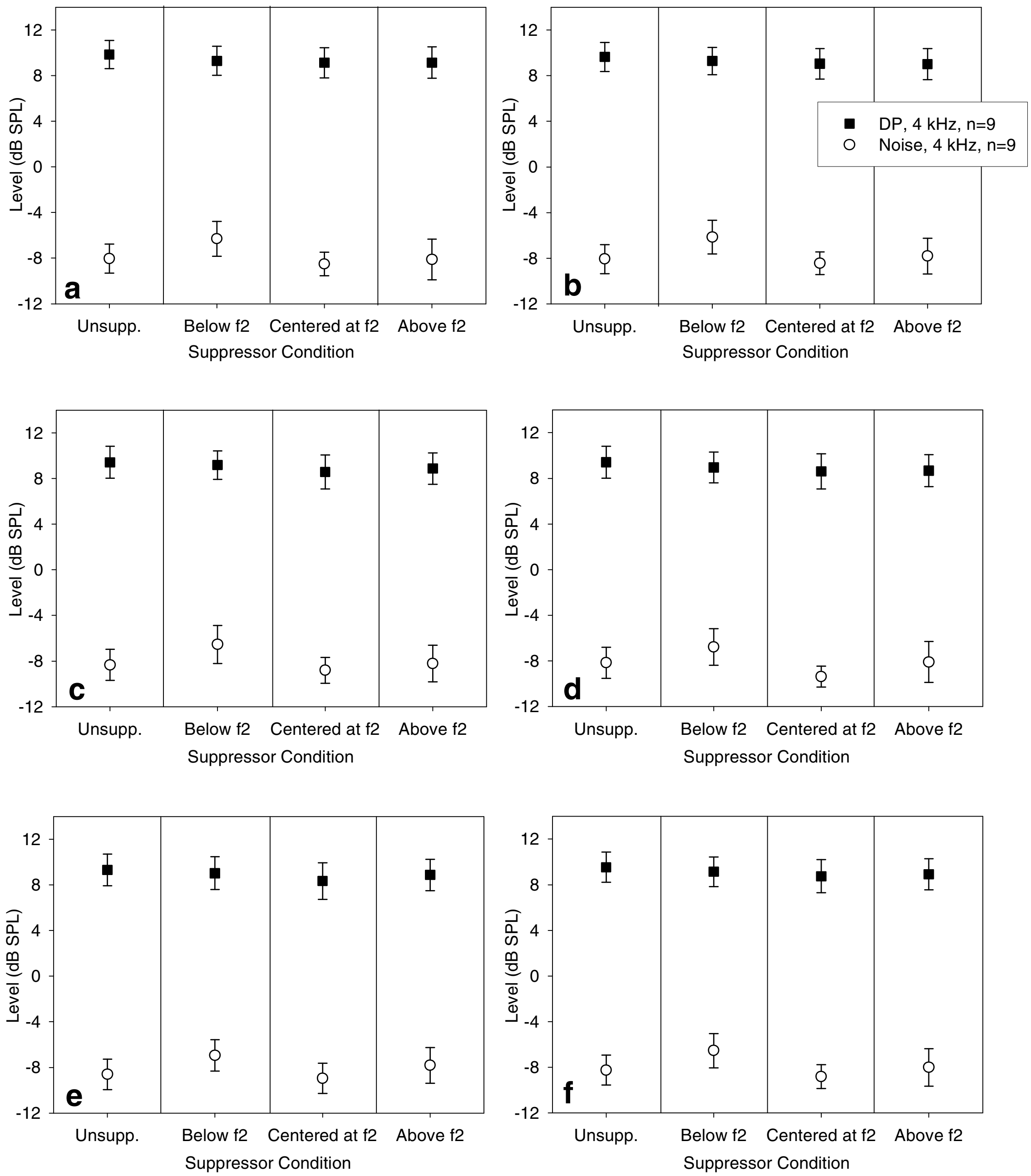

Figure 20. Mean DPOAE levels and noise levels are shown for the nine participants who provided usable data for f2 = 4000 Hz in Experiment 2. Mean levels for the four suppressor conditions are shown separately for each of the five runs included in analysis (panels a – e) and averaged across the five runs (panel f). Error bars represent one standard error of the mean.

ANOVA with two within-subject factors: suppressor condition (four levels) and run (five levels). Tests of within-subjects effects showed no main effect of suppressor condition [$F(3,24) = 1.518$, $p > .05$], or run [$F(4, 32) = 1.70$, $p > .05$], and there was no interaction between suppressor condition or run [$F(12, 96) = .568$, $p > .05$].

Magnitude of suppression. As in Experiment 1, data for Experiment 2 were also analyzed using a derived dependent variable of magnitude of suppression in order to facilitate comparison with previously published studies. Magnitude of suppression was calculated by subtracting the mean of each participant's suppressed DPOAE levels for each suppressor condition from the mean of her unsuppressed DPOAE levels, resulting in three levels of the suppressor condition factor. Run was not a factor in these analyses, because DPOAE levels from the five runs in each condition were averaged to calculate a single value for each suppressor condition within each participant.

Figure 21 shows the magnitudes of suppression for the subset of seven participants who provided usable data for both f2 = 2000 Hz and f2 = 4000 Hz. This subset was analyzed to investigate whether an effect of f2 frequency would be observed in the magnitudes of suppression. A repeated measures design with two factors was used: suppressor condition (three levels) and f2 frequency (two levels – 2000 Hz and 4000 Hz). There were no significant main effects of f2 frequency [$F(1,6) = .332$, $p > .05$] and suppressor condition [$F(2,12) = 1.997$, $p > .05$] and no interaction between these factors [$F(2,12) = .204$, $p > .05$].

The analysis of magnitude of suppression was run separately for f2 = 2000 Hz and f2 = 4000 Hz to include all available data in each f2 frequency condition.

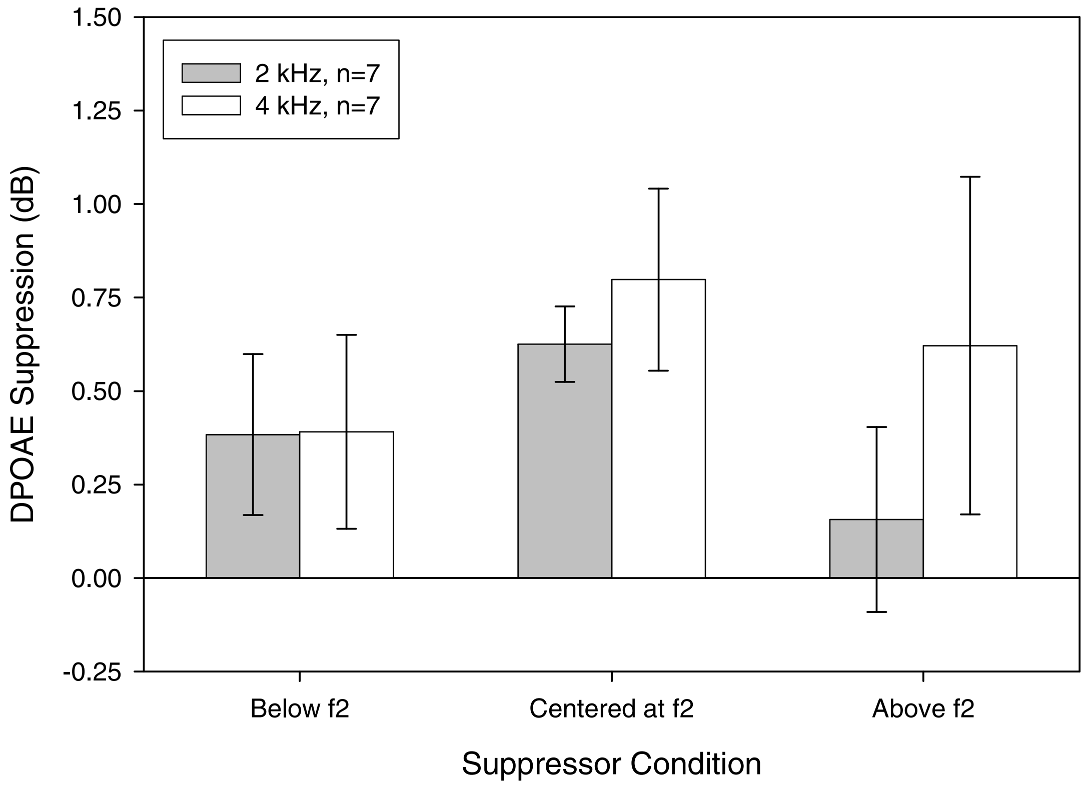

Figure 21. Mean magnitude of DPOAE suppression is shown for each suppressor condition for the subset of seven participants who provided usable data for both f2 = 2000 Hz and f2 = 4000 Hz in Experiment 2. Error bars represent one standard error of the mean.

Figure 22 shows the mean magnitude of suppression data for the three suppressor conditions for f2 = 2000 Hz (panel a) and f2 = 4000 Hz (panel b). The same repeated measures design was used, with just one factor: suppressor condition (three levels). For f2 = 2000 Hz, a significant main effect of suppressor condition was found [$F(2, 16) = 4.207$, $p < .05$]. Planned Helmert contrasts revealed no significant difference between the mean magnitude of suppression when the suppressor was centered at the f2 frequency compared to the mean magnitudes of suppression when suppressors were centered ½ octave below and ½ octave above f2 [$F(1,8) = 3.927$, $p > .05$]. However, the suppressor centered below the f2 frequency resulted in a significantly greater magnitude of suppression than the suppressor centered above the f2 frequency [$F(1, 8) = 5.483$, $p < .05$]. The lack of significance in the first contrast (suppressor centered at f2 frequency vs. mean of suppressors centered below and above f2 frequency) and presence of significance in the second contrast (suppressor centered below f2 frequency vs. suppressor centered above f2 frequency) seems unexpected based on the graphical display of the means. This pattern of results may be related to the larger standard deviation in the first contrast (.54) compared to the standard deviation in the second contrast (.30). No significant main effect of suppressor condition was found for f2 = 4000 Hz, [$F(2,16) = .633$, $p > .05$]. The large standard deviations evident in the means in each condition, particularly in the suppressor condition with the narrowband noise located ½ octave above the f2 frequency, may have contributed to this lack of statistical significance.

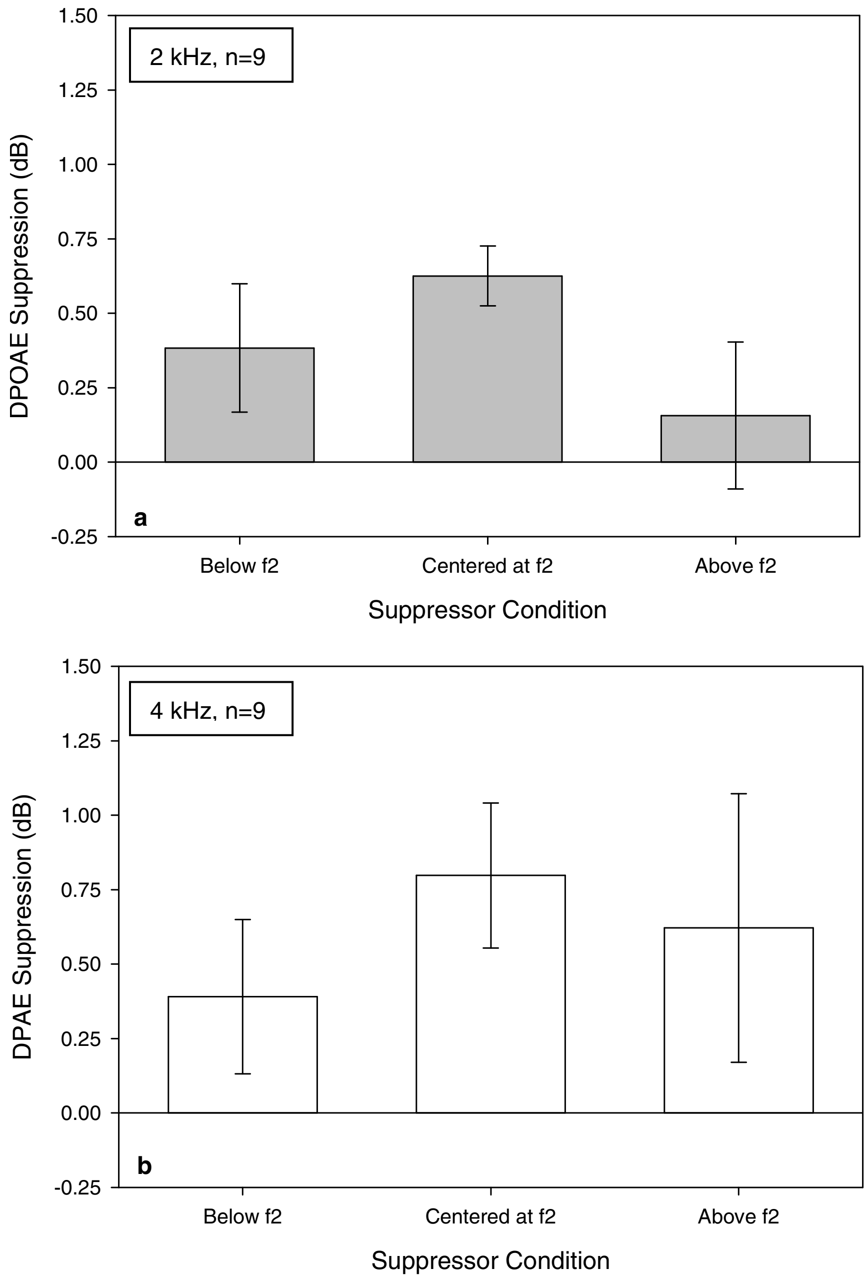

Figure 22. Panel (a) shows mean magnitude of DPOAE suppression achieved by each suppressor condition for f2 = 2000 Hz, and panel (b) shows mean magnitude of suppression achieved by each suppressor condition for f2 = 4000 Hz for all participants who provided usable data in Experiment 2. Error bars represent one standard error of the mean.

Effect of SOAEs. Only two participants in each f2 frequency condition in Experiment 2 did not have present SOAEs. Therefore, statistical analysis of the effect of SOAEs was not conducted.

The results of Experiment 2 demonstrate that when the narrowband noise suppressor was centered at an f2 of 2000 Hz, resulting DPOAE levels were significantly lower than in the other three conditions. This finding was not significant for f2 = 4000 Hz, but standard deviations were larger for f2 = 4000 Hz than for f2 = 2000 Hz. These larger standard deviations may have obscured any potentially significant findings. The results of Experiment 2 also corroborate the results from Experiment 1 by demonstrating that significant DPOAE suppression can be recorded with at least some noise suppressors presented in a forward masking paradigm. As in Experiment 1, the f2 frequency had no significant effect on the results.

Chapter 6: Discussion

The results of this study demonstrate that a significant reduction in DPOAE level can be measured using an ipsilateral forward masking paradigm. This result is particularly important because there have thus far been no published studies which have investigated this specific paradigm using DPOAEs. Rather, related studies have utilized contralateral simultaneous suppression of DPOAEs and TEOAEs (e.g., Maison, et al., 2000; Puel & Rebillard, 1990; Williams & Brown, 1997), ipsilateral simultaneous suppression of DPOAEs (e.g., Abdala et al., 1996; Gorga et al., 2003), ipsilateral and contralateral forward masking of TEOAEs (Berlin et al., 1995), and even ipsilateral DPOAE adaptation (e.g., Bassim, Miller, Buss, & Smith, 2003; Kim et al., 2001; Liberman et al., 1996).

Because existing OAE suppression studies all have fundamental differences compared to this investigation, direct comparisons to other reported results are somewhat difficult. However, the magnitudes of suppression recorded in this investigation are comparable to those reported in related work. In the widest bandwidth suppressor condition in Experiment 1, a mean of .72 dB of suppression was achieved for f2 = 2000 Hz, and a mean of .86 dB was achieved for f2 = 4000 Hz (see Figure 13). This magnitude of suppression is consistent with that reported by Maison et al. (2000) in their investigation of suppressor bandwidth effects on contralateral simultaneous suppression of tone pip TEOAEs. Their published graphs show approximately .6 to .8 dB of suppression for suppressor bandwidths comparable to the widest bandwidths used in Experiment 1. Berlin et al. (1995) also reported comparable magnitudes of suppression in their study of TEOAEs, in which a white noise suppressor preceded a series of four clicks. They reported that ipsilateral presentation of the noise yielded slightly more suppression than contralateral presentation, but in both conditions the magnitude of suppression was around 1 dB. Furthermore, investigations of ipsilateral DPOAE adaptation in humans have also revealed means of approximately 1 dB or less of reduction in DPOAE level, with the majority of this decrease attributed to activity of the MOC system (Bassim et al., 2003; Kim et al., 2001). The MOC system is considered to be the source of contralateral OAE suppression as well as ipsilateral suppression when the ipsilateral suppressor and stimuli do not overlap in time (Berlin et al., 1995; Maison et al., 2000).

Larger magnitudes of suppression than those found in the present study are typically observed in recordings of simultaneous ipsilateral DPOAE suppression tuning curves (e.g., Abdala et al., 1996; Gorga et al., 2003). A portion of the larger magnitudes of suppression typically observed in these simultaneous paradigms might be due to the fact that the suppressor remains on throughout the duration of data recording, resulting in no decay of the suppressive effects during averaging. However, the simultaneous suppressor presentation likely involves an additional mechanism as well. Psychophysical studies have consistently shown different patterns of responses from simultaneous and non-simultaneous masking paradigms, with simultaneous paradigms resulting in a broader shape to the tuning curve (e.g., Moore, 1978; Moore & Glasberg, 1981). This difference has also been observed in physiological studies of neural firing rates (Delgutte, 1990). It has been suggested that simultaneous masking includes the effects of two-tone suppression in addition to the excitatory response, while the lateral suppressive effect (i.e., two-tone suppression) is not present in the results measured with non-simultaneous paradigms (Moore & Glasberg, 1982; Moore & Vickers, 1997). In the case of DPOAE suppression tuning curves with simultaneous tonal maskers, it may be that the two-tone suppression mechanism is adding to the magnitude of OAE reduction recorded. Investigating methods to assess frequency characteristics of DPOAE suppression in a forward masking paradigm will help shed light on the effects of these different processes, their effects on objectively measured DPOAE suppression, and their influence on auditory function.

Experiment 1: Effect of Suppressor Bandwidth

This experiment was designed as a preliminary investigation of the effect of suppressor bandwidth on ipsilateral suppression of DPOAEs when the suppressor offset precedes the onset of the stimulus tones. There have thus far been no published reports of investigations using this ipsilateral forward masking paradigm for DPOAE suppression. Simultaneous DPOAE suppression paradigms have shown strong dependence on suppressor frequency characteristics (e.g., Abdala et al., 1996; Gorga et al., 2003), and these results have been interpreted as providing useful information about cochlear frequency tuning. The goal of the present study was to observe the frequency tuning present when the suppressor was separated from the stimulus tones in a forward masking paradigm. This forward masking paradigm removed at least some intracochlear effects, so that any frequency specificity would more likely be attributable to the activity of the MOC system.

Planned comparisons designed to test the hypothesized pattern of suppression with increasing suppressor bandwidth (according to the conceptualized ERB) revealed no significant differences. Therefore, this preliminary study provides no evidence that the frequency tuning of the MOC system corresponds to the sharp frequency tuning achieved within the cochlea. Rather, given the lack of statistically significant differences between suppressor conditions, it seems that the frequency tuning measured by this paradigm may be quite broad. This pattern of results was the same for f2 = 2000 Hz and f2 = 4000 Hz.

In addition to the present study, there have been several other investigations of frequency tuning of the MOC, though each of those studies used a different suppressor paradigm. The combined results of those investigations have been mixed, with at least two studies reporting some limited frequency specificity (one of them relating it to the psychoacoustic ERB) (Chéry-Croze et al., 1993; Neumann et al., 1997) and at least two studies reporting very broad frequency tuning (Lilaonitkul et al., 2002; Maison et al., 2000).

Despite the consistent lack of significance between suppressor conditions for these analyses, a look at the graphs of the means (Figures 12 and 13) reveals another consistent observation: for each of these analyses, magnitude of suppression appears to increase with increasing bandwidth. Due to the lack of statistical significance between the suppressed DPOAE levels at the different suppressor bandwidths, the theoretical importance of this observation should be interpreted cautiously. However, it may hint at a subtle effect of suppressor bandwidth that is not being detected in the current study. The effect size observed in this study is quite small (mean suppression less than 1 dB), while the standard deviations are relatively large. This combination of factors may be obscuring any true differences between the conditions. Future studies may focus on determining the stimulus and masker parameters that will maximize the magnitude of suppression, allowing subtle differences between suppressor conditions to be observed more easily. It is expected in OAE research to encounter a certain degree of variability in OAE levels, which makes the relatively large standard deviations observed in this study unsurprising. Including a larger number of participants in future studies may help overcome the statistical effects of the large standard deviations.

An investigation of differences between participants with present or absent SOAEs was not part of the primary experimental questions. However, it has been reported that presence or absence of SOAEs can affect characteristics of evoked OAEs (e.g., Moulin et al., 1993; Penner & Zhang, 1997). Therefore, data from Experiment 1 were analyzed to see whether any differences in DPOAE levels and magnitude of suppression existed between individuals with a least one SOAE present in the test ear compared to participants without any SOAEs. Only three participants for each f2 frequency in Experiment 1 had no SOAEs, thus the no-SOAE group was very small. This proportion of participants without SOAEs is consistent with estimates of the prevalence of SOAEs in young adult females with normal hearing (Penner & Zhang, 1997). Nevertheless, significant differences were observed in the overall DPOAE levels between the groups. Participants with SOAEs had larger DPOAE levels in all suppressor conditions, including the unsuppressed condition, compared to participants without SOAEs. This finding is consistent with studies reporting larger evoked OAE levels for participants with SOAEs compared to those without. It has been suggested that the presence of SOAEs has an additive effect on evoked OAEs (Kulawiec & Orlando, 1995; Moulin et al., 1993; Ozturan & Oysu, 1999).

There were, however, no significant differences in magnitude of suppression between the two groups. Therefore, there is no evidence from this study to suggest this paradigm yields different suppressive effects for participants with and without SOAEs. It should be noted that the no-SOAE group in the present study had much larger standard deviations than the SOAE group (see Figures 14 and 15); this may be related to the small number of participants in the no-SOAE group. There has been at least one previous report of differences in SOAE suppression results from participants with and without SOAEs. Neumann et al. (1997) reported that participants with SOAEs demonstrated larger magnitudes of suppression on average compared to the participants without SOAEs. Furthermore, they reported that the close correspondence between ERBs estimated from notched-noise suppressed TEOAEs and ERBs estimated from a similar psychoacoustic masking paradigm only existed for the six participants with SOAEs in that study. The TEOAE suppression over-estimated ERB for the three participants with no present SOAEs compared to the psychoacoustic estimate. Like the present study, Neumann et al. (1997) did not investigate differences related to SOAE presence or absence as a primary research question, and they also had only three participants without SOAEs. Further work must be done to investigate specifically whether presence or absence of SOAEs affects magnitude of suppression and what information that might provide about auditory function.

Experiment 2: Effect of Suppressor Center Frequency

The aim of this preliminary investigation was to discover whether a forward masking paradigm would yield a similar masking pattern to that observed in simultaneous DPOAE suppression tuning curves, with the greatest effect on DPOAE level occurring when the suppressor was centered at the f2 frequency, a lesser effect on DPOAE level occurring for suppressors centered ½ octave below the f2 frequency, and the least effect for suppressors centered ½ octave above the f2 frequency. Suppression tuning curves of DPOAEs have traditionally been recorded using an ipsilateral pure tone suppressor that is varied across frequencies above and below the f2 frequency (e.g., Abdala et al., 1996; Gorga et al., 2003), and they have been touted as a means of investigating frequency characteristics of cochlear functioning. These STCs have been measured with simultaneous suppressors, yet psychophysical measurements of tuning curves have consistently found differences between simultaneous and forward masked PTCs, with forward masked PTCs suggesting sharper frequency tuning (e.g., Moore, 1978). This difference has been explained as the presence of suppression in the simultaneous condition, with suppression in this context referring to a decrease in the neural response to an incoming sound in the presence of another sound (i.e., two-tone suppression, or lateral suppression) (Delgutte, 1990) rather than a reduction in DPOAE level. On the other hand, because two-tone suppression does not linger following the termination of the stimulus, forward masking is suggested to represent a more purely excitatory response area

(Delgutte, 1990). Certainly, because DPOAE generation requires two simultaneous pure tone stimuli, the presence of two-tone suppression from the two stimulus tones cannot be eliminated. However, investigations of auditory nerve fibers have suggested that the strongest two-tone suppressive effects occur for tones closer in frequency than the primary frequencies used in the present study (Javel, McGee, Walsh, Farley, & Gorga, 1983). Removing the suppressor as a simultaneous factor and instead presenting it in a forward masked paradigm might provide some insight into how these different mechanisms interact with the frequency characteristics of the MOC system for DPOAE generation and suppression.

Helmert analysis of the full dataset for f2 = 2000 Hz showed that the suppressor centered at the f2 frequency yielded significantly lower DPOAE levels than the combined means of the other three suppressors. This is consistent with findings from DPOAE STCs showing the tip of the STC located at or near the f2 frequency. There was no significant difference between the unsuppressed condition and the mean of the suppressor conditions centered above and below the f2 frequency; however, the suppressor located below the f2 frequency yielded significantly lower DPOAE levels compared to the suppressor located above the f2 frequency. This particular finding would be consistent with results from DPOAE STCs, because the low frequency tail of the STC typically has a shallower slope than the high frequency tail, indicating a greater effectiveness of maskers lower in frequency than the f2 compared to those higher in frequency than the f2 (e.g., Abdala et al., 1996; Gorga et al., 2003).

Despite the significant results for f2 = 2000 Hz, no main effect of suppressor condition was found for f2 = 4000 Hz. However, the standard deviations for f2 = 4000 Hz were larger than for f2 = 2000 Hz. Perhaps this contributed to the lack of statistical significance.

Overall results from Experiment 2 suggest that an effect of suppressor center frequency on DPOAE suppression is observable in a forward masking paradigm, at least for an f2 of 2000 Hz. As expected from STC literature, the greatest observed suppression of the DPOAE level occurred when the suppressor was located at the f2 frequency. This is also in agreement with the current conceptualization of DPOAE generation, which suggests that location of the main source of DPOAE generation is near the f2 frequency (e.g., Kalluri & Shera, 2001; Pienkowski & Kunov, 2001). While the particular paradigm used in Experiment 2 may depend as much on the DPOAE generation site as on general frequency tuning per se, results for f2 = 2000 Hz do reveal a definite frequency-specific relationship. Not all frequency bands are equally effective in DPOAE suppression. This provides evidence for some degree of frequency-specific function of the MOC system as it relates to outer hair cell mediation.

Based on the promising results of the present study, it will be useful for future studies to include a greater number of suppressor center frequencies to add to the results reported here. While an effect of suppressor center frequency was observable in the present paradigm for f2 = 2000 Hz, further work is needed to define the parameters that will maximize this effect.

Effect of f2 Frequency

No main effect of f2 frequency or interaction between frequency and suppressor condition or run was found for DPOAE level in either Experiment 1 or Experiment 2. This same lack of significance was found when the data were analyzed as magnitude of suppression. The graphs of the DPOAE levels across the four suppressor conditions appear to suggest small differences in DPOAE amplitude between the f2 = 2000 Hz and f2 = 4000 Hz conditions; however, the larger standard deviations in the f2 = 4000 Hz condition may be responsible for the lack of statistical significance. A main effect of f2 frequency on DPOAE level would not have addressed the hypotheses of these experiments, because it would have provided information about overall differences in DPOAE amplitudes between frequencies. On the other hand, the absence of a significant interaction between f2 frequency and suppressor condition in the analysis of DPOAE levels suggests that f2 frequency did not alter the effect a suppressor had on the resulting DPOAE levels. This result was further supported by the lack of a significant main effect or interaction of f2 frequency for the analysis of magnitude of suppression.

This lack of significance was expected in Experiment 1, because the bandwidths used were all based on the ERB for each f2 frequency, and the estimated ERB by definition takes into account differences between frequencies. However, it was hypothesized that there would be significant differences between DPOAE levels observed at the two f2 frequencies for Experiment 2 in the different suppression conditions. Specifically, it was hypothesized that suppressors located ½ octave above and below the f2 frequency of 4000 Hz would provide less suppression than those located ½ octave above and below the f2 frequency of 2000 Hz. This pattern of differences would support PTC and STC results suggesting sharper tuning for higher frequencies (Abdala et al., 1996; Kummer et al., 1995). While statistical analyses revealed no main effect of f2 frequency and no interactions with f2 frequency, the pattern of significance for f2 = 2000 Hz and f2 = 4000 Hz differed when data were analyzed separately for each f2 frequency. A main effect of suppressor condition was found for f2 = 2000 Hz but not for f2 = 4000 Hz in both analyses of DPOAE level and magnitude of suppression. However, a look at the mean magnitudes of suppression for f2 = 2000 Hz and f2 = 4000 Hz shows similar trends across the suppressor conditions (see Figures 21 and 22). The larger standard deviations present in the f2 = 4000 Hz data compared to the f2 = 2000 Hz data may be responsible for the lack of significance of suppressor condition for f2 = 4000 Hz despite the significance found for f2 = 2000 Hz.

Stimulus frequency has been shown to influence results in previous OAE suppression studies. In an investigation of the effect of contralateral noise suppressor bandwidth on the suppression of tone pip OAEs, Maison et al. (2000) reported no significant main effect of frequency between 1000 Hz and 2000 Hz tone pip/suppressor noise center frequencies. However, they did report a significant interaction between the center frequencies and the suppressor bandwidth, with the magnitude of suppression caused by increasing suppressor bandwidth greater for 2000 Hz than 1000 Hz. The lack of significance found in Experiment 1 is not inconsistent with these results due to several important differences in suppressor characteristics between the two studies. Maison et al. (2000) did not base their suppressor bandwidths on estimates related to cochlear tuning (such as the ERB), but rather selected bandwidths based on increments of octaves. They also included much wider bandwidths than were used in Experiment 1. In addition to the spectral implications of the wider frequency range, the suppressor noise at the widest bandwidths had higher overall intensities than were used in Experiment 1, so differential effects of noise levels between the two studies cannot be ruled out. It is also not clear from their report whether the authors considered the potential effect of the acoustic reflex during broadband stimulation with their highest-level suppressors. Activation of the acoustic reflex would stiffen the middle ear system, attenuating the OAE levels prior to their arrival in the ear canal. The acoustic reflex has been shown to exert differential effects depending on frequency (Pang & Guinan, 1997), so this possibility should not be ruled out as a contributing factor to their results.

Based on their published graphs, the greatest magnitudes of suppression occurred with bandwidths significantly wider than those used in Experiment 1 (Maison et al., 2000). Perhaps if the suppressor bandwidths used in the present study had been extended over such a wide frequency range, similar differences between f2 frequencies would have been evident. However, using such a wide bandwidth suppressor in a DPOAE paradigm would have overlapped the f1 and 2f1-f2 frequencies in addition to the f2 frequency, and this was specifically avoided in the present study in order to narrow the focus to the area around the f2 frequency.

Maison et al. (2000) also included a greater number of suppressor bandwidths than was used in the present study, and this may have increased their ability to observe differences. Perhaps including a greater number of suppressor bandwidths, both narrower than and wider than those included in the present study, might provide a greater opportunity for observing differences in f2 frequencies in future studies. Finally, it should also be noted that Maison et al. (2000) recorded TEOAEs in a simultaneous contralateral suppression paradigm, while the present study measured DPOAEs and presented suppressors ipsilaterally in a forward masking paradigm. DPOAEs and TEOAEs have fundamental differences in the stimuli required for their generation and in the resulting emissions that are recorded. Unlike TEOAEs, the DPOAE emission of interest (2f1-f2) occurs at a frequency that is distinct from either of the two stimulus tones. The suppressors used in Experiments 1 and 2 did not overlap the frequency region corresponding to the frequency of the measured emission. This fundamental difference in the frequency relationships between TEOAEs and DPOAEs may influence the effect frequency has on OAE suppression. Further research is required to more fully explore this possibility.

Differences between f2 frequencies have also been demonstrated in recordings of DPOAE STCs suggesting that, similar to PTCs, STC width narrows with increasing f2 frequency (e.g., Abdala et al., 1996; Kummer et al., 1995). Experiment 2 has elements reminiscent of STC paradigms, though there are clearly important differences. STCs are traditionally recorded ipsilaterally with simultaneous pure tone suppressors stepped in frequency around f2 and increased in level until a criterion magnitude of suppression is achieved. In Experiment 2, the suppressors were narrowband noise, were presented prior to stimulus onset, were only presented at three center frequencies, and were only presented at one pre-determined level. In spite of these fundamental differences, it was expected that a significant difference in f2 frequencies would be observed that would be consistent with the sharper DPOAE STCs reported for higher f2 frequencies. There may be several reasons for the lack of a significant difference between f2 frequencies in Experiment 2. First, the standard deviations in the f2 = 4000 Hz condition were much larger than those in the f2 = 2000 Hz condition, and this may have interfered with the ability to find statistical significance. Second, only three suppressor center frequencies were included. Perhaps these three points were not located at the ideal frequency regions for observing a difference between f2 frequencies. Specifically, the suppressors located above and below the f2 frequency may have been located too close to or too distant from the f2 frequency to provide an assessment that is sensitive enough to reveal differences in the effect of f2 frequency. The use of contiguous or even overlapping noise bands may be required to provide a more detailed picture of any interactions between suppressor center frequencies and f2 frequencies that were too subtle to observe in the present study.

General Discussion and Future Directions

The magnitude of the DPOAE suppression achieved in Experiments 1 and 2 was relatively small, and this small effect size, while not inconsistent with that found in similar studies, may make it more difficult to observe subtle differences between suppressor conditions, particularly as the limited designs used in the present study are expanded to provide a more detailed look at the effects demonstrated here. One way to increase the magnitude of observed suppression might be to use lower levels of primary tones. The levels used in this study (f1 = 65 dB SPL and f2 = 55 dB SPL) were chosen for several reasons. First, those levels are commonly used in both clinical and research domains, so considerable evidence has been reported relating to their measurement. Second, evidence suggests that similar levels produce robust levels of 2f1-f2 emissions (e.g., Hauser & Probst, 1991; Kummer et al., 2000). Lastly, the formula used in this study to estimate ERB (Glasberg & Moore, 1990) was created from psychophysical results generated in response to stimuli of similar moderate levels. Therefore, it was desirable to apply the formula to stimuli similar to the levels for which it was intended. However, it has been suggested that cochlear nonlinearity is more active at lower levels and that there is a saturating effect in the peripheral auditory channels as stimulus level increases (e.g., Abdala, 2000; Dallos, 1992). Estimates of psychoacoustic tuning curves have been reported to differ according to stimulus levels, with sharper tuning at lower stimulus levels (e.g., Nelson, Chargo, Kopun, & Freyman, 1990). Similarly, Gorga et al. (2003) report that DPOAE STCs were sharper when measured with lower level stimulus tones. It has also been suggested that the efferent effects on TEOAE suppression are stronger at lower stimulus intensities (Hood, Berlin, Hurley, Cecola, & Bell, 1994; Moulin, Collet, & Morgon, 1992). Future investigations will be useful to identify the parameters that obtain the largest magnitudes of suppression in this paradigm.

It seems likely that stimulus and suppressor parameters may play a large role in the magnitude of MOC activation. It has been theorized that the MOC system may function to enhance audibility of transient signals in background noise (Kawase, Delgutte, & Liberman, 1993; Micheyl & Collet, 1996; Winslow & Sachs, 1988). Therefore, stimulus parameters which most closely mimic such situations may elicit the strongest MOC response. Indeed, it has been suggested that temporally varying acoustic stimuli may maximally stimulate MOC activity, and greater OAE suppression has been reported for modulated compared to steady acoustic stimulation (Maison, Micheyl, & Collet, 1997; Maison, Micheyl, & Collet, 1999). These results were obtained in simultaneous contralateral conditions, so it would be useful to observe whether similar results would be obtained in an ipsilateral condition. A forward masking paradigm would provide a valid means to compare these effects been ipsilateral, contralateral, and even binaural conditions.

Future investigations might also extend the findings presented here by observing the DPOAE suppression over time. Berlin et al. (1995) analyzed the changes in level over time in OAEs elicited by a series of four clicks over 60 ms which were preceded by 408 ms of white noise. They reported that the greatest magnitude of suppression occurred between 8 and 18 ms following the onset of the first click, after which time suppression magnitude decreased. Similarly, results from psychoacoustic studies of forward masking have demonstrated significant decay of masking as the time between signal and masker is increased (e.g., Moore & Glasberg, 1983a). Thus selection of the stimulus duration for Experiments 1 and 2 involved a necessary compromise: the longer the duration, the more any suppressive effects could be obscured due to decay of the suppression effect during averaging, but the shorter the duration, the greater the risk of transient energy contaminating the DPOAE recording with excessive noise. The total duration of the stimulus tones used in these experiments was 40 ms, and DPOAE levels were averaged throughout the 30 ms full amplitude portion of the stimulus tones. This corresponds to the time period 10-40 ms after the offset of the suppressor noise. If the magnitude of suppression decreased significantly over that 30 ms recording window, then the final DPOAE level derived from the averages across those 30 ms might underestimate the maximum magnitude of suppression achieved in the first few milliseconds following stimulus onset. Therefore, recording DPOAE level as a function of time throughout the stimulus duration would provide useful information regarding the time course of recovery from suppression. Additionally, recording DPOAE level over time might reduce the need for such brief-duration stimuli as those used in the present study.

The 40 second total duration (30 second full amplitude duration) of the primary tones used in this study was unconventionally short for DPOAE recordings (e.g., Gorga et al., 1993; Wagner, Heppelmann, Müller, Janssen, & Zenner, 2007). This brief duration is a likely explanation for the relatively high mean noise levels recorded in the present experiments, compared to those reported in many published studies (e.g., Gorga et al., 1993; Gorga et al., 1994; Gorga et al., 1997) (see Table 3). The mean noise levels in the unsuppressed DPOAE recordings averaged across both Experiment 1 and Experiment 2 were –4.0 dB SPL for f2 = 2000 Hz and –8.1 dB SPL for f2 = 4000 Hz. Gorga and colleagues often report noise floors of –20 to –30 dB SPL in their published studies (e.g., Gorga et al., 1993; Gorga et al., 1997). Thus the very brief stimulus durations used in this study might have caused the overall higher noise levels and might have contributed to the noise contamination observed in the data that did not meet the "clean" criterion for use in data analysis. However, for the data that were included in analysis, no significant main effects or interactions were found for the noise levels in either experiment for both f2 = 2000 Hz and f2 = 4000 Hz. This suggests that the noise levels, despite being higher than is typical, did not have a significant influence on the DPOAE levels used in analysis. Additionally, the mean noise levels for the same f2 frequencies were very close between Experiment 1 and Experiment 2 (see Table 3). This suggests that the noise levels associated with the runs used in analysis remained reasonably stable within a consistent range across both experiments. The finding of higher noise levels in the f2 = 2000 Hz condition compared to the f2 = 4000 Hz condition corresponds to typical noise patterns in OAE recordings showing greater levels of noise present in lower frequencies compared to higher frequencies (e.g., Gorga et al., 1993; Gorga et al., 1997).

While the noise levels recorded in these studies are higher than those reported in many published studies, the DPOAE levels are consistent with previous reports of DPOAE levels in listeners with normal hearing (e.g., Abdala et al., 1996; Gorga et al., 1993; Lonsbury-Martin, Harris, Hawkins, Stagner, & Martin, 1990) (see Table 3). This suggests that the DPOAEs recorded in this paradigm and included in the analysis were robust despite the higher noise floors. Additionally, no significant effect of run on DPOAE level was found for Experiment 1, f2 = 4000 Hz or for both f2 frequencies in Experiment 2. This is important, because it shows that the DPOAE levels used in analysis were relatively stable over time. While statistical analysis identified a significant main effect of run in Experiment 1, f2 = 2000 Hz, post hoc analysis did not show any significant differences between any of the runs, and inspections of the graphs of individual data do not raise any suspicions of an effect of run. These observations are interpreted to suggest that the effect of run in Experiment 1, f2 = 2000 Hz may have been inflated in the main analysis. Due to the random presentation order of the conditions, the data points used for each participant in each suppressor condition occurred at different, yet reasonably overlapping, points in data collection, so this analysis of run effect is somewhat artificial. However, it still provides a useful verification that there are likely no unintended effects emerging due to changes in DPOAE levels over time.

One particular strength of this study is that all participants, prior to inclusion in data collection, underwent evaluation of their acoustic stapedial reflex threshold to broadband noise. One participant was excluded from data collection because her reflex to broadband noise was not high enough above the level of the suppressor noise used in this study. This strategy was used to rule out any influence of the acoustic reflex on observed results. While animal studies commonly avoid this possibility by severing the middle ear muscles (e.g., Liberman & Brown, 1986; Puel & Rebillard, 1990), this same solution is clearly not applicable in humans. Thus while some OAE suppression articles include a mention of the acoustic reflex as a potential, if unlikely, concern in their discussions, most make no a priori attempts to avoid eliciting it (e.g., Maison et al., 2000; Neumann et al., 1997; Wagner, et al., 2007; Williams & Brown, 1997). Nevertheless, even with the conservative inclusion criterion used in this investigation, acoustic reflex effects too small to be observed with standard clinical immittance equipment cannot be completely ruled out. Any such effect, however, is likely to be negligible.

The number of participants included in this study is consistent with many published articles in this research area (e.g., Berlin et al., 1995; Neumann et al., 1997; Williams & Brown, 1997); however, given the small effect sizes and large standard errors observed in the present study, including greater numbers of participants in future studies may help enhance the ability to observe significant changes.

There are several advantages to recording DPOAE suppression using an ipsilateral forward masking paradigm. Contralateral suppression is a commonly used research tool, but ipsilateral suppression can provide different and complementary information. The ipsilateral efferent response is considered to be stronger than the contralateral response (Liberman & Guinan, 1998), and while this difference appears large in animal studies (Brown, 1989; Liberman & Brown, 1986), the limited evidence available in human studies suggests that the effect, while present, may not be as large in humans (Berlin et al., 1995). Measurement of ipsilateral OAE suppression tests pathways and neurons in the MOC that are not tested in a contralateral paradigm. Used in isolation, ipsilateral OAE suppression can provide insight into the function of what may be the largest component of the MOC efferent system and perhaps provide a larger effect than the same paradigm in a contralateral condition. Used in conjunction with the more commonly used contralateral suppression, the addition of ipsilateral suppression can provide a more comprehensive evaluation of MOC system function and may clarify the relative strengths of these ipsilateral and contralateral effects in humans.

Contralateral OAE suppression has been commonly recorded with suppressor and stimulus tone(s) presented simultaneously. Results obtained from the present study cannot be compared directly to results from similar ipsilateral paradigms, because different mechanisms are involved. An ipsilateral simultaneous presentation would create intracochlear effects such as two-tone suppression in addition to MOC effects, while the contralateral presentation would measure purely effects from the MOC system. However, comparing DPOAE suppression from ipsilateral and contralateral suppressors would be of theoretical interest to examine the complex nature of the MOC feedback loop to the cochlea in ipsilateral and contralateral pathways. Presentation of an ipsilateral suppressor in a forward masking paradigm likely avoids obvious intracochlear effects and provides a cleaner representation of MOC function. Such results could be compared directly to those obtained using contralateral suppressors in a forward masking paradigm to reveal differences in the ipsilaterally and contralaterally responsive feedback loops. Berlin et al. (1995) reported one such comparison for click-evoked TEOAEs, and the present study shows that such a comparison would be possible using DPOAEs as well.

While OAE suppression remains as yet primarily a research tool, further research into aspects of OAE suppression may ultimately translate this knowledge into a standard clinical tool. The MOC system has been shown to play a role in detecting high frequency transient signals in noise, and therefore it is thought to play a significant role in enhancing speech understanding in background noise (Liberman & Guinan, 1998; Micheyl & Collet, 1996). Evidence for abnormalities in OAE suppression has been reported in disorders of auditory processing (Muchnik et al., 2004) and in auditory neuropathy/dyssynchrony (Hood et al., 2000). An effect of aging on contralateral DPOAE suppression has been reported by Kim et al. (2002); they suggested that magnitude of DPOAE suppression may be more sensitive than unsuppressed DPOAE levels to age-related changes in the auditory system. Therefore, a comprehensive understanding of the characteristics of OAE suppression, elicited not only with the commonly used contralateral suppressors, but also with the ipsilateral forward masking suppressors described in this report, is important to enhance our understanding of the normal auditory system and may one day commonly aid evaluation of the disordered auditory system.

The main findings from this investigation are:

1. Narrowband noise suppressors presented in an ipsilateral forward masking paradigm effectively reduce the amplitude of DPOAEs.
2. The bandwidth of a narrowband noise suppressor in the ipsilateral forward masking paradigm used in this study has little effect on the amplitude of the DPOAE.
3. The center frequency of a narrowband noise suppressor in the ipsilateral forward masking paradigm does have a significant effect on the amplitude of the DPOAE, at least for f2 = 2000 Hz. When the noise suppressor was centered at the f2 of 2000 Hz, DPOAE levels were significantly lower compared to all other conditions. Additionally, DPOAE levels were significantly lower when the suppressor noise was centered ½ octave below the f2 frequency of 2000 Hz compared to when the suppressor was centered ½ octave above 2000 Hz.

Chapter 7: Conclusions

The results of this investigation provide the first evidence of DPOAE suppression measured using an ipsilateral forward masking paradigm. This paradigm allows investigation of ipsilateral effects of MOC mediation on cochlear function without the additional effects of intracochlear interactions and two-tone suppression that may occur in simultaneous ipsilateral paradigms. Results from Experiment 1 are not consistent with sharp frequency tuning in the MOC system and are not aligned with estimates of auditory filter width derived from psychoacoustic investigations. Rather, they support previous evidence that MOC activation is broadly tuned and integrates inputs from a wide range of frequencies. Therefore, the sharp frequency tuning present in the cochlea seems not to be preserved in the efferent portion of the MOC feedback loop.

Results from Experiment 2 are consistent with results from other paradigms indicating that narrowband noise suppressors centered around the stimulus frequency generate more suppression than narrowband suppressors centered more remotely from the stimulus frequency. This suggests some degree of frequency specificity within the MOC system, in that auditory stimulation in more distant frequency regions does not alter the behavior of the outer hair cells in the region of the stimulus.

No significant differences were present between the two pairs of primary tones tested, suggesting that the MOC activity elicited using the current paradigm did not behave differently in the regions of 2000 Hz and 4000 Hz. Results provide preliminary evidence that the frequency-specific MOC activation involved in DPOAE suppression is more broadly tuned than the frequency tuning of the cochlea. Future investigations will be important to continue exploring this paradigm and to determine the stimulus and suppressor parameters that will produce the most valuable results to answer a variety of research questions relating to the strength and frequency tuning of the MOC system and how it influences cochlear activity.

Appendix A

Consent Form

Initials _______ Date ______

CONSENT FORM

Project Title	*Temporal Processing Measured with Otoacoustic Emissions*
Why is this research being done?	*This is a research project being conducted by Dr. Sandra Gordon-Salant and Erin McAlister at the University of Maryland, College Park. We are inviting you to participate in this research because you are at least 18 years of age and you are not currently experiencing any hearing loss. The purpose of this research is to develop new measures of auditory system function that will extend our knowledge of inner ear function and could be useful in identifying auditory processing limitations in difficult-to-test patients.*
What will I be asked to do?	*The procedures involve preliminary tests and experimental tests. The preliminary tests are a questionnaire about hearing health history and a routine hearing test. The experimental tests will present sounds to your ear canal and will automatically measure a response. You will be asked to sit quietly during the experimental tests. The experimental tests should last about 1 hour and 45 minutes, and the preliminary tests should last about 45 minutes. You will be permitted to take breaks if you wish. Testing will be completed in one or two sessions, if you prefer. The research will take place in the Hearing Science Lab at the University of Maryland, College Park.*
What about confidentiality?	*We will do our best to keep your personal information confidential. To help protect your confidentiality: (1) your name will not be included on the collected data; (2) a code will be placed on the collected data; (3) through the use of an identification key, the researcher will be able to link your data to your identity; and (4) only the researcher and her graduate research assistant will have access to the identification key. If we write a report or article about this research project, your identity will be protected to the maximum extent possible.* *Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.*
What are the risks of this research?	*There are no known risks associated with the experiment.*
What are the benefits of this research?	*This research is not designed to help you personally, but the results may help the investigator learn more about auditory temporal processing using otoacoustic emissions. One benefit you will receive is a free hearing test.*
Do I have to be in this research? **Can I stop participating at any time?**	*Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify.*

Project Title	*Temporal Processing Measured with Otoacoustic Emissions*
Is any medical treatment available if I am injured?	*The University of Maryland does not provide any medical, hospitalization or other insurance for participants in this research study, nor will the University of Maryland provide any medical treatment or compensation for any injury sustained as a result of participation in this research study, except as required by law.*
What if I have questions?	*This research is being conducted by Dr. Sandra Gordon-Salant and Erin McAlister at the University of Maryland, College Park. If you have any questions about the research study itself, please contact Dr. Gordon-Salant at: Department of Hearing and Speech Sciences, University of Maryland, LeFrak Hall, 301-405-4225, sgordon@hesp.umd.edu* *If you have questions about your rights as a research subject or wish to report a research-related injury, please contact:* **Institutional Review Board Office, University of Maryland, College Park, Maryland, 20742; (e-mail) irb@deans.umd.edu; (telephone) 301-405-0678** *This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.*
Statement of Age of Subject and Consent	*Your signature indicates that:* *you are at least 18 years of age;,* *the research has been explained to you;* *your questions have been answered; and* *you freely and voluntarily choose to participate in this research project.*
Signature and Date	**NAME OF SUBJECT**
	SIGNATURE OF SUBJECT
	DATE

IRB APPROVED
VALID UNTIL
MAY 1 8 2007
UNIVERSITY OF MARYLAND
COLLEGE PARK

Appendix B

Hearing History Questionnaire

HEARING HISTORY QUESTIONNAIRE

Subject # ______________ Age ________ Hearing Status _________

Subjective: Hearing History

A. Do you have any problem hearing? ___ Yes ___ No

Which ear? ___ Right ___ Left ___ Both

When did you first notice it? ____________

Has the hearing loss been: ___ Gradual ___ Sudden ___ Fluctuating

B. Do you wear a hearing aid? ___ Yes ___ No

How long have you worn it? _____________

Are you satisfied with it? ________________

C. Do you ever hear any noises in your ears? ___ Yes ___ No

Describe: ____ Ringing ____ Roaring ____ Buzzing ____ Humming

____ Chirping ____ Pulsing ____ Hissing ____ Other

These noises are in: ___ Right ear ___ Left ear ___ Both ears

When did you start having the noises? ___________________________

D. Have you had any dizziness? ___ Yes ___ No

Which of the following describes your dizziness?

___ The room seems like it's spinning and I'm still

___ I feel like I'm spinning and the room is still

___ I feel lightheaded

___ I feel like I'm going to fall down

___ I feel sick to my stomach

___ I feel off-balance in space

___ Other

When did you start feeling dizzy? ______________________________

Is your dizziness caused by any particular body movement? ___ Yes ___ No

What movement? ____

The dizziness is present ___ Always ___ Often ___ Sometimes

E. Do you have a feeling of fullness or pain in your ears? ___ Yes ___ No

That feeling is present ___ Always ___ Often ___ Sometimes

The feeling is present in ___ Right ear ___ Left ear ___ Both

When did you start having that feeling? ____________________

Otologic History

A. Have you had repeated ear infections? ___ Yes ___ No

Which ear? ___ Right ___ Left ___ Both ___ Can't remember

B. Are you presently being treated by and ear specialist? ___ Yes ___ No

For what reason? ____

C. Have you ever had surgery on your ears? ___ Yes ___ No

Type of surgery ______________________

Date of surgery ______________________

D. Have you ever been exposed to loud noises? ___ Yes ___ No

Please indicate the types of noise:

___ Gunfire
___ Explosion
___ Factory noise
___ Power tools
___ Heavy equipment
___ Other types ____________________________

___ Motorcycles
___ Power lawn mowers
___ Aircraft
___ Loud music
___ Military tanks

Do you think that noise has affected your hearing? ___ Yes ___ No

Family History

Has any blood relative that you know of had a hearing loss? ___ Yes ___ No

What was the cause of the hearing loss? ____________________________

How was the(se) person(s) related to you?

_____ Father
_____ Mother
_____ Sister
_____ Brother

_____ Grandmother
_____ Grandfather
_____ Aunt

_____ Uncle
_____ Cousin
_____ Child

General Medical History

A. Health at present can be described as _______________

B. Do you have diabetes? ___ Yes ___ No

Age at onset ________________

Treatment (diet, drugs, etc.) ________________

C. Do you have high blood pressure? ___ Yes ___ No

Approximate age at onset ________________

Treatment ________________

D. Do you have heart or kidney disease? ___ Yes ___ No

Type and age of onset ________________

Treatment ________________

E. Please indicate which of the following diseases you have had. State approximate age or date of onset.

____ Measles	____ Rheumatic Fever	____ Malaria	____ Pneumonia
____ Mumps	____ Scarlet Fever	____ TB	____ Severe Burns
____ Chickenpox	____ Diphtheria	____ Cancer	____ Other
____ Polio	____ Meningitis	____ Epilepsy	
____ Valley Fever	____ Venereal Disease	____ Jaundice	

F. Do you take any medication regularly? ___ Yes ___ No

Type and Dosage ________________

____

____

G. Do you smoke cigarettes or cigars? ___ Yes ___ No

How much do you smoke per day? (Packs) ________

How long have you been smoking? (Years) ________

H. Do you drink alcohol? ___ Regularly ___ Socially ___ Never

I. Have you ever been diagnosed with a learning disability? ___ Yes ___ No

Have you ever received special education services? ___ Yes ___ No

Has anyone in your family ever received special education services? ___Yes ___ No

J. Do you have musical Training? ______ Yes ______ No

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