Lack of association between contralateral inhibition of otoacoustic emissions and vowel formant discrimination in noise

Ian B. Mertes[a*] and Kristin M. Johnson[a]

[a]*Department of Speech and Hearing Science, University of Illinois at Urbana-Champaign, Champaign, Illinois, United States of America*

*Contact: imertes@illinois.edu

Lack of association between contralateral inhibition of otoacoustic emissions and vowel formant discrimination in noise

Purpose: The medial olivocochlear (MOC) reflex enhances neural encoding of signals in noise, and measurement of its function may hold clinical utility. Previous research on how the reflex aids speech-in-noise perception has been equivocal. Motivated by animal work, we examined associations between MOC reflex activity and formant discrimination in noise in humans to better understand how the MOC reflex contributes to audition. We hypothesized that participants with stronger MOC reflex activity would have better formant discrimination in noise abilities.

Method: Twenty-six normal-hearing listeners met all inclusion and exclusion criteria (mean age = 21.5 years), with data from 25 participants included in the final analysis. Transient-evoked otoacoustic emissions (TEOAEs) were measured in right ears. MOC reflex activity was assessed using a contralateral inhibition paradigm in which the change in TEOAE amplitude without versus with a contralateral MOC reflex elicitor was computed. Formant discrimination thresholds for a synthetic vowel /ɛ/ were obtained in right ears using a two-alternative forced-choice procedure that adaptively varied the second formant frequency. Discrimination thresholds were obtained at three signal-to-noise ratios (SNRs).

Results: TEOAE amplitudes were significantly reduced in the presence of the reflex elicitor ($p < 0.05$). Discrimination thresholds decreased significantly with increasing SNR ($p < 0.05$ in all cases). No significant correlations were found between contralateral inhibition measures and discrimination thresholds at any SNR ($p > 0.05$ in all cases).

Conclusion: Contrary to hypothesis, no significant associations were found between contralateral inhibition and formant discrimination in noise performance. It is possible that the MOC reflex contributes to formant discrimination but not in a monotonic fashion. Future work should consider investigating how the MOC reflex contributes to other perceptual properties to better characterize the functional relevance of the MOC reflex.

Keywords: olivocochlear; MOC; contralateral suppression; formant discrimination

Introduction

The mammalian auditory system contains descending pathways that modify the function of the auditory periphery. The medial olivocochlear (MOC) reflex pathway is an interface between the brainstem and outer hair cells. For a recent review of the MOC system, see Lopez-Poveda [1]. When MOC neurons are stimulated, they decrease gain of the cochlear amplifier, which is beneficial for encoding sounds in background noise [2].

The MOC reflex is activated by both steady-state and fluctuating noises [3,4], suggesting that it contributes to listening in daily noisy situations. The MOC reflex can be measured using a contralateral inhibition paradigm in which the change in otoacoustic emission (OAE) amplitude is quantified without versus with a contralateral MOC activator [5]. Otoacoustic emissions are soft sounds generated as a byproduct of outer hair cell amplification of sound [6] and are influenced by activity of the MOC reflex. Contralateral inhibition measurements may be clinically useful for assessing the source of auditory difficulties for a variety of conditions including auditory neuropathy spectrum disorder [7], auditory processing disorder [8], hearing difficulties despite a normal audiogram [9], myasthenia gravis [10], and smoking [11]. A review of the potential clinical utility of contralateral inhibition testing can be found in Murdin and Davies [12].

A number of studies have found that contralateral inhibition is associated with better speech-in-noise performance [13–15]. However, some studies have shown no significant correlation [16–18]. Speech perception is a complex phenomenon, and so examining different psychoacoustic tasks in isolation may point to specific process to which the MOC reflex contributes. A lesion study in cats indicated that sectioning the MOC bundle impaired discrimination of the second formant (F2) of synthetic vowel stimuli presented in background noise [19]. Vowel perception is important to consider because vowels contribute to the perception of running speech [20] and listeners with hearing loss encounter difficulty with correct identification of vowels [21]. The purpose of the current study was to determine the extent to which MOC reflex activity is involved in vowel formant discrimination in adults with normal hearing. We hypothesized that stronger contralateral inhibition would be associated with better formant discrimination in noise abilities due to an MOC-mediated decrease in masking.

Materials and Methods

Participants

The protocol was approved by the university's Institutional Review Board. Written informed consent was obtained from all participants. Participants received either monetary compensation or extra credit for an approved university course. Eligible participants consisted of males and females ages 18 to 40 years old who reported no hearing loss or otologic issues. Participants were also required to be right-handed to maximize the magnitude of contralateral inhibition [22]. Eligible participants had an unremarkable otoscopic examination, 226-Hz tympanograms within normal clinical limits, air-conduction thresholds ≤20 dB HL at octave frequencies from 250–8000 Hz, no air-bone gaps exceeding 10 dB at two or more consecutive octave frequencies from 500–4000 Hz, and measurable TEOAEs in the right ear from 1000–4000 Hz. A total of 26 participants met all inclusion and exclusion criteria (25 females; mean age ± SD = 21.5 ± 3.5 years). However, data from one participant were excluded from the analysis due to a software error during the formant discrimination task that resulted in one extra presentation of a stimulus condition. Eight additional participants did not meet all inclusion/exclusion criteria due to outer or middle ear issues.

Equipment

Testing took place in a single-walled sound-treated booth (WhisperRoom, Inc., Morristown, TN, USA). The experimental setup consisted of a Windows-based PC that interfaced with a Babyface Pro 24-bit sound card (RME, Haimhausen, Germany) and MATLAB ver. 2018a (The MathWorks, Inc., Natick, MA, USA). A sampling rate of 44100 Hz was used for all stimulus generation and response acquisition. Contralateral inhibition testing was conducted using an ER-10C probe microphone (Etyōmtic Research, Elk Grove Village, IL, USA) with +20 dB of microphone gain, an ER-2 insert earphone (Etyōmtic Research), and the software utility ARLas [23]. The formant discrimination task involved a touch screen monitor and ER-2 insert earphones. Statistical analyses were performed using MATLAB and SPSS ver. 26.0.0.0 (IBM Corp., Armonk, NY, USA).

Contralateral Inhibition

Participants were seated in a recliner for the measurements and watched videos on a tablet computer with the sound turned off to reduce physiologic noise of the participants and to maintain their attention. Clicks were presented to the right ear at 65 dB pSPL at 20/s. 2400 sweeps were obtained. Responses were filtered from 1000–4000 Hz. Artifacts were considered to be responses with an amplitude exceeding 1.5 times the interquartile range and were rejected. Responses were analyzed in the time window from 8–18 ms. Mean signal and noise floor waveforms were obtained using the two-buffer technique [24]. TEOAEs were considered present if the signal-to-noise ratio (SNR) exceeded 6 dB and the whole-wave reproducibility exceeded 70%. Contralateral inhibition was assessed by measuring TEOAEs without and with contralateral acoustic stimulation (CAS- and CAS+, respectively) using an interleaved paradigm. The CAS consisted of broadband noise presented to the left ear at 60 dB SPL. Contralateral inhibition was quantified as the decibel difference in root-mean-square amplitude between the TEOAE waveforms obtained without versus with CAS. Positive values denoted inhibition and larger values denoted a stronger MOC reflex. No participants exhibited probable middle ear muscle reflex activation based on the critical differences in stimulus amplitude measured in the ear canal for CAS- versus CAS+ [25].

Formant Discrimination

The formant discrimination task used stimulus parameters adapted from Hienz et al. [19] with modifications based on our preliminary testing in human participants. The synthetic vowel /ɛ/ was created in MATLAB using a cascade synthesizer [26]. The fundamental frequency was 100 Hz. Formant frequencies with bandwidths in parentheses were: F1 = 500 Hz (60 Hz); F2 = 1700 Hz (90 Hz); F3 = 2500 Hz (200 Hz); F4 = 3300 Hz (200 Hz); F5 = 3750 Hz (200 Hz). The vowel stimuli were presented at 50 dB(A) to minimize the possibility of evoking the ipsilateral MOC reflex. The vowel duration was 400 ms including 10-ms ramps. Discrimination thresholds were obtained using a three-interval, two alternative forced choice paradigm. All stimuli were presented in the right ear through an ER-2 insert earphone while the left ear was occluded with a foam earplug. Participants were instructed to select the interval (two or three) that sounded different from the first interval. Participants were first presented a reference stimulus (F2 = 1700 Hz) followed by two stimuli: an identical reference stimulus and a probe stimulus that always had a higher F2 frequency (see Figure 1 for example spectra). The inter-stimulus interval was 400 ms. The order of presentation for the second reference stimulus and the probe stimulus was randomly selected at each trial. On-screen text regarding whether the response was correct or incorrect was displayed after each trial.

Participants first completed a brief practice session with no background noise to orient them to the task. After the practice, participants completed the discrimination task in the presence of speech-shaped noise. The noise amplitude was varied to yield SNRs of -3 dB, 0 dB, and +3 dB. The difference in F2 frequency between the probe and reference, ΔF2, was initially set at 80 Hz. The procedure began with a 1-down, 1-up staircase method with a ΔF2 step size of 4 Hz. Following the first reversal, a 2-down, 1-up staircase method with a ΔF2 step size of 2 Hz was used to target 70.7% correct performance [27]. At each SNR, participants completed 10 reversals. Threshold was computed as the mean ΔF2 across the last six reversals. The order of SNRs was randomized for each participant.

Results

Box plots revealed one or more outliers in the distribution of TEOAE amplitudes and noise floors across participants, as evidenced by data points that fell outside 1.5 times the box width. Therefore, nonparametric tests were used to compare results between the CAS+ and CAS- conditions. A Wilcoxon signed-rank test revealed that TEOAE amplitude was significantly lower in CAS+ (*Mdn* = 0.729 dB SPL) than in CAS- (*Mdn* = 3.297 dB SPL), $z = 4.197$, $p < 0.0005$. A Wilcoxon signed-rank test also revealed that there was no significant difference in TEOAE noise floor between CAS+ (*Mdn* = -20.944 dB SPL) and CAS- (*Mdn* = -21.192 dB SPL), $z = -0.243$, $p = 0.808$. A box plot revealed one outlier in the distribution of contralateral inhibition data across participants. Median contralateral inhibition was 2.854 dB (range = -0.989 to 6.737 dB, IQR = 1.788 dB).

Figure 2 displays mean discrimination thresholds across SNRs. Thresholds were normally distributed at all SNRs and the assumption of sphericity was met. A one-way repeated measures ANOVA revealed a statistically significant difference in threshold across SNR, $F(2,48) = 28.913$, $p < 0.0005$, partial $\eta^2 = 0.546$. Post-hoc testing with Bonferroni correction revealed that threshold decreased significantly from -3 to 0 dB SNR [13.136 Hz (95% CI = 6.152 to 20.120 Hz), $p <$

0.0005], from 0 to +3 dB SNR [5.984 Hz (95% CI = 0.424 to 11.544) Hz, $p = 0.032$], and from -3 to +3 dB SNR [19.120 Hz (95% CI = 11.923 to 26.317 Hz), $p < 0.0005$].

Scatterplots of discrimination thresholds as a function of contralateral inhibition at each SNR are shown in Figure 3. Due to the presence of an outlier in the contralateral inhibition data, the associations between contralateral inhibition and discrimination thresholds at each SNR were assessed using Spearman rank correlations. Results revealed no significant correlations at -3 dB SNR [$r_s(23) = -0.059$, $p = 0.779$], 0 dB SNR [$r_s(23) = -0.024$, $p = 0.912$], or +3 dB SNR [$r_s(23) = -0.255$, $p = 0.219$].

Discussion

The contralateral inhibition and discrimination threshold results were as expected. TEOAE amplitudes decreased in CAS+, consistent with a number of studies. The amplitude decrease, along with lack of probable middle ear muscle reflex activation, suggests that the MOC reflex was functional in this participant sample. Participants demonstrated a range of contralateral inhibition values, consistent with other work [28]. The decrease in discrimination threshold with increasing SNR is also consistent with past research [29].

Our finding of a lack of significant correlation between MOC reflex activity and formant discrimination thresholds at any SNR is in contrast to the findings of Hienz et al. [19] who found that surgical lesioning of the MOC bundle caused a significant increase in discrimination thresholds in cats at poor SNRs. Animal models allow for such experimental control over physiologic processes, whereas we were limited to a correlational investigation. It is possible that the MOC reflex contributes to vowel discrimination in noise but that there is not a monotonic relationship between a TEOAE-based metric of the MOC reflex functioning and the formant discrimination threshold. It is also possible that a relationship may have been apparent had we included a larger range of hearing levels (e.g., listeners with slight or mild sensorineural hearing loss) that would increase the variability in both MOC reflex strength and discrimination thresholds. It must also be considered that activation of the MOC reflex can broaden cochlear tuning due to a decrease in cochlear amplifier gain [30,31], which could be detrimental to the formant discrimination task. If this were the case, it could be expected that stronger MOC reflex activity would be associated with larger discrimination thresholds (i.e., a positive correlation would be present). One explanation for the lack of correlation in the current study is that the increased antimasking may be effectively canceled out by broadened cochlear tuning, at least for this particular task.

We acknowledge some limitations to the experimental approach. The formant discrimination task was designed so that F2 differences would be readily perceptible and were based on pilot testing on laboratory members and several enrolled participants. The vowel duration used here is longer than the typical duration [32]. Regarding the training period, it has been established that lower thresholds are obtained after long training durations [33]. We avoided prolonged training in an attempt to minimize potential top-down effects of training that could modulate the strength of the MOC reflex during the experiment [34]. It must be noted that the initial seven participants completed 50 trials of practice, while the remaining participants completed 15 minutes of practice (mean = 200 trials) based on Liu and colleagues [35]. Visual inspection revealed no apparent differences in discrimination thresholds as a function of training, and separate analyses of the participants who completed 15 minutes of training still revealed non-significant correlations between MOC reflex strength and discrimination thresholds. Future work in this area should carefully consider balancing the need for training on the perceptual task with the possibility of modifying the MOC reflex strength as a result of the training. Measurement of the MOC reflex before and after the perceptual task could allow for detection of training-mediated changes in MOC reflex function.

Assessment of the MOC reflex may hold utility both for understanding auditory mechanisms as well as clinical assessment, such as site-of-lesion testing [12]. Based on the results of the current study, the formant discrimination in noise task did not demonstrate a significant monotonic relationship with the strength of the MOC reflex. A future direction of this research program is to focus on the relationship between the MOC reflex and other tasks relevant to the perception of speech. Candidates include gap detection, amplitude modulation detection, and listening effort, with the overarching goals of understanding the functional role of the MOC reflex in individuals with normal hearing and with sensorineural hearing loss and developing clinically-feasible assessments of the MOC reflex.

Disclosure statement

The authors report no conflict of interest.

Acknowledgments

The authors thank Dr. Eric D. Young for providing MATLAB code for the cascade synthesizer. This work was supported by the Office of the Vice Chancellor for Research at the University of Illinois at Urbana-Champaign under an Arnold O. Beckman award. Portions of this work were presented at the 46th Annual Scientific and Technology Conference of the American Auditory Society, February 28 to March 2, 2019, Scottsdale, AZ, USA. The MOC reflex recordings were previously analyzed in a recent publication from our group [25]. However, the current study describes a new analysis and application of these data.

References

[1] Lopez-Poveda EA. Olivocochlear efferents in animals and humans: From anatomy to clinical relevance. Front Neurol. 2018;9:197.

[2] Kawase T, Delgutte B, Liberman MC. Antimasking effects of the olivocochlear reflex. II. Enhancement of auditory-nerve response to masked tones. J Neurophysiol. 1993;70:2533–2549.

[3] Kalaiah MK, Nanchirakal JF, Kharmawphlang L, et al. Contralateral suppression of transient evoked otoacoustic emissions for various noise signals. Hear Bal Comm. 2017;15:84-90.

[4] Mertes IB. Human medial efferent activity elicited by dynamic versus static contralateral noises. Hear Res. 2018;365:100–109.

[5] Collet L, Kemp DT, Veuillet E, et al. Effect of contralateral auditory stimuli on active cochlear micro-mechanical properties in human subjects. Hear Res. 1990;43:251–261.

[6] Kemp DT. Stimulated acoustic emissions from within the human auditory system. J Acoust Soc Am. 1978;64:1386–1391.

[7] Hood LJ, Berlin CI, Bordelon J, et al. Patients with auditory neuropathy/dys-synchrony lack efferent suppression of transient evoked otoacoustic emissions. J Am Acad Audiol. 2003;14:302–313.

[8] Morlet T, Nagao K, Greenwood LA, et al. Auditory event-related potentials and function of the medial olivocochlear efferent system in children with auditory processing disorders. Int J Audiol. 2019;58;213–223.

[9] Tokgoz-Yilmaz S, Kose SK, Turkyilmaz MD, et al. The role of the medial olivocochlear system in the complaints of understanding speech in noisy environments by individuals with normal hearing. Auris Nasus Larynx. 2013;40:521–524.

[10] Ralli M, di Stadio A, Greco A, et al. Development of progressive hearing loss and tinnitus in a patient with myasthenia gravis: an overlooked comorbidity? Hear Bal Comm. 2017;15:260–266.

[11] Prabhu P, Kumar P, Goyal S, et al. Influence of smoking on contralateral suppression of distortion product otoacoustic emissions. Hear Bal Comm. 2017;15:72–75.

[12] Murdin L, Davies R. Otoacoustic emission suppression testing: a clinician's window onto the auditory efferent pathway. Audiol Med. 2008;6:238–248.

[13] Giraud AL, Garnier S, Micheyl C, et al. Auditory efferents involved in speech-in-noise intelligibility. Neuroreport. 1997;8:1779–1783.

[14] Kumar UA, Vanaja CS. Functioning of olivocochlear bundle and speech perception in noise. Ear Hear. 2004;25:142–146.

[15] Mertes IB, Johnson KM, Dinger ZA. Olivocochlear efferent contributions to speech-in-noise recognition across signal-to-noise ratios. J Acoust Soc Am. 2019;145:1529–1540.

[16] Wagner W, Frey K, Heppelmann G, et al. Speech-in-noise intelligibility does not correlate with efferent olivocochlear reflex in humans with normal hearing. Acta Otolaryngol. 2008;128:53–60.

[17] Stuart A, Butler AK. Contralateral suppression of transient otoacoustic emissions and sentence recognition in noise in young adults. J Am Acad Audiol. 2012;23:686–696.

[18] Yashaswini L, Maruthy S. The influence of efferent inhibition on speech perception in noise: A revisit through its level-dependent function. Am J Audiol. 2019;2:508–515.

[19] Hienz RD, Stiles P, May BJ. Effects of bilateral olivocochlear lesions on vowel formant discrimination in cats. Hear Res. 1998;116:10–20.

[20] Cole RA, Yan Y, Mak B, et al. The contribution of consonants versus vowels to word recognition in fluent speech. In: 1996 IEEE International Conference on Acoustics, Speech, and Signal Processing Conference Proceedings; 1996 May 7–10; Atlanta, GA. Piscataway (NJ): Institute of Electrical and Electronics Engineers; 1996. p. 853–856.

[21] Van Tasell DJ, Fabry DA, Thibodeau LM. Vowel identification and vowel masking patterns of hearing- impaired subjects. J Acoust Soc Am. 1987;81:1586–1597.

[22] Khalfa S, Veuillet E, Collet L. Influence of handedness on peripheral auditory asymmetry. Eur J Neurosci. 1998;10:2731–2737.

[23] Goodman SS [Internet]. ARLas: Auditory Research Lab audio software. Version 2017.11.04. Iowa City (IA): University of Iowa; 2017. Available from: https://github.com/myKungFu/ARLas.

[24] Prieve BA, Gorga MP, Schmidt A, et al. Analysis of transient- evoked otoacoustic emissions in normal- hearing and hearing- impaired ears. J Acoust Soc Am. 1993;93:3308–3319.

[25] Mertes IB. Establishing critical differences in ear-canal stimulus amplitude for detecting middle ear muscle reflex activation during olivocochlear efferent measurements. Int J Audiol. 2020;59:140–147.

[26] Klatt DH. Software for a cascade/parallel formant synthesizer. J Acoust Soc Am. 1980;67:971–995.

[27] Levitt H. Transformed up- down methods in psychoacoustics. J Acoust Soc Am. 1971;49:467–477.

[28] Backus BC, Guinan JJ. Measurement of the distribution of medial olivocochlear acoustic reflex strengths across normal-hearing individuals via otoacoustic emissions. J Assoc Res Otolaryngol. 2007;8:484–496.

[29] Liu C, Kewley-Port D. Formant discrimination in noise for isolated vowels. J Acoust Soc Am. 2004;116:3119–3129.

[30] Vinay, Moore BC. Effects of activation of the efferent system on psychophysical tuning curves as a function of signal frequency. Hear Res. 2008;240:93–101.

[31] Mishra SK, Dinger Z. Influence of medial olivocochlear efferents on the sharpness of cochlear tuning estimates in children. J Acoust Soc Am. 2016;140:1060–1071.

[32] Hillenbrand JM, Clark MJ, Houde RA. Some effects of duration on vowel recognition. J Acoust Soc Am. 2000;108:3013–3022.

[33] Kewley-Port D. Vowel formant discrimination II: Effects of stimulus uncertainty, consonantal context, and training. J Acoust Soc Am. 2001;110:2141–2155.

[34] de Boer J, Thornton AR. Neural correlates of perceptual learning in the auditory brainstem: efferent activity predicts and reflects improvement at a speech-in-noise discrimination task. J Neurosci. 2008;28:4929–4937.

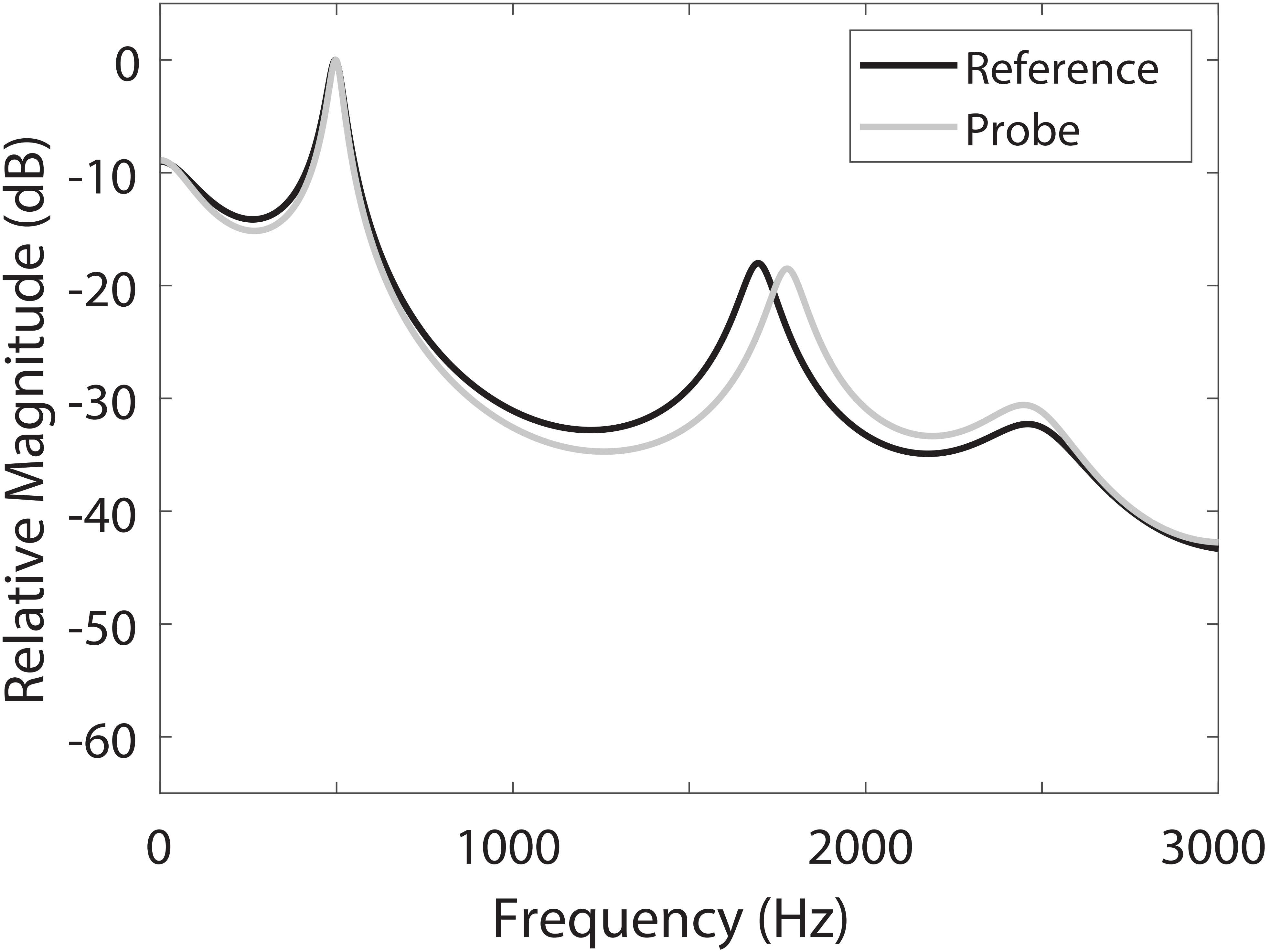
[35] Liu C, Tao S, Wang W, et al. Formant discrimination of speech and non-speech sounds for English and Chinese listeners. J Acoust Soc Am. 2012;132:EL189–EL195.

Figure 1. Spectral envelopes of the reference stimulus (F2 = 1700 Hz) and an example probe stimulus (F2 = 1780 Hz). Envelopes were obtained using linear predictive coding via the MATLAB function ‘lpc.m’.

Figure 2. Mean discrimination thresholds at each SNR. Error bars represent 1 standard deviation.

Figure 3. Scatter plots of discrimination thresholds as a function of contralateral inhibition. Each panel shows data for a different SNR as indicated at the top of the panel.

Figure



Reference
Probe
0
-10
-20
-30
-40
-50
-60
Relative Magnitude (dB)
0
1000
2000
3000
Frequency (Hz)

Figure 2

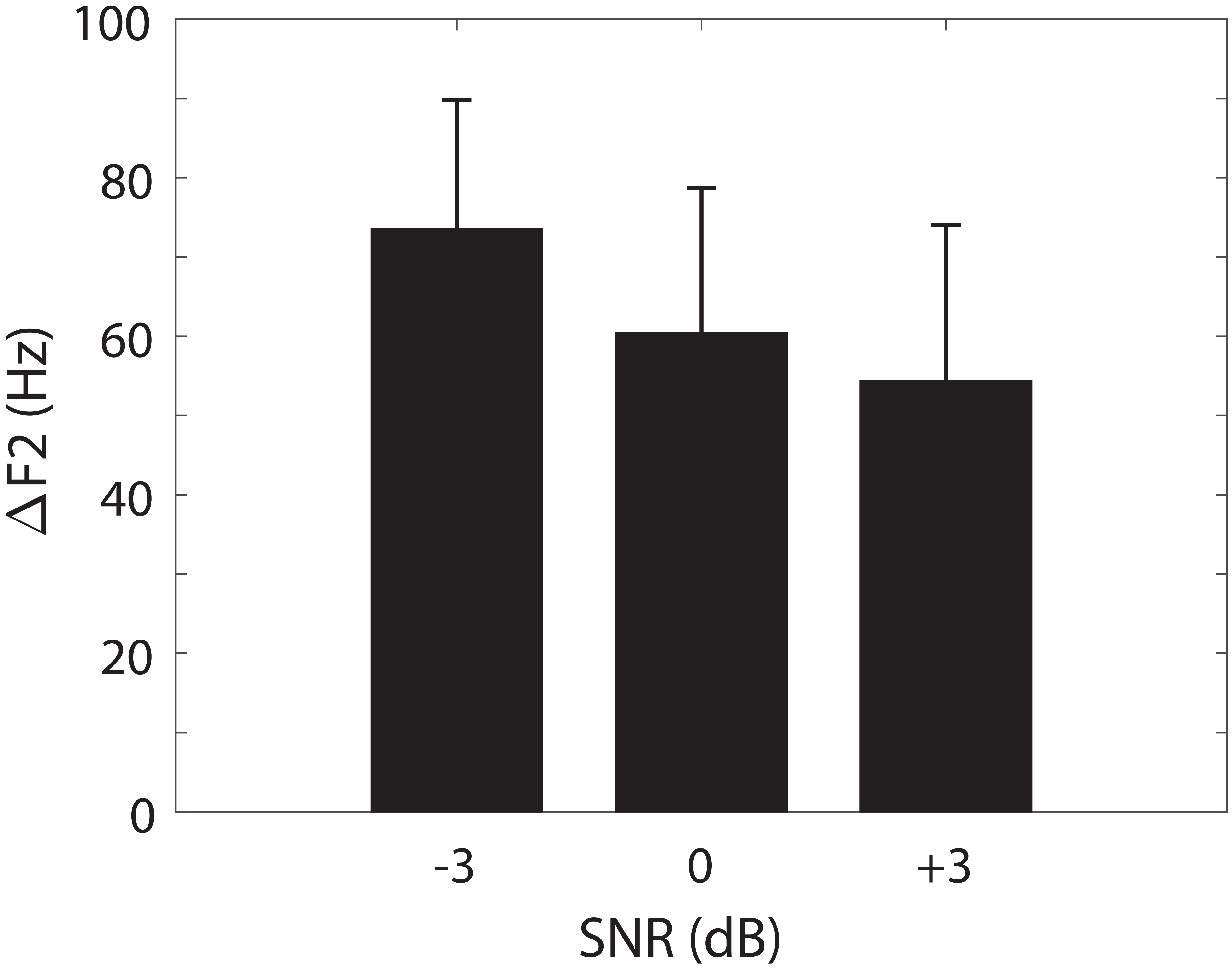
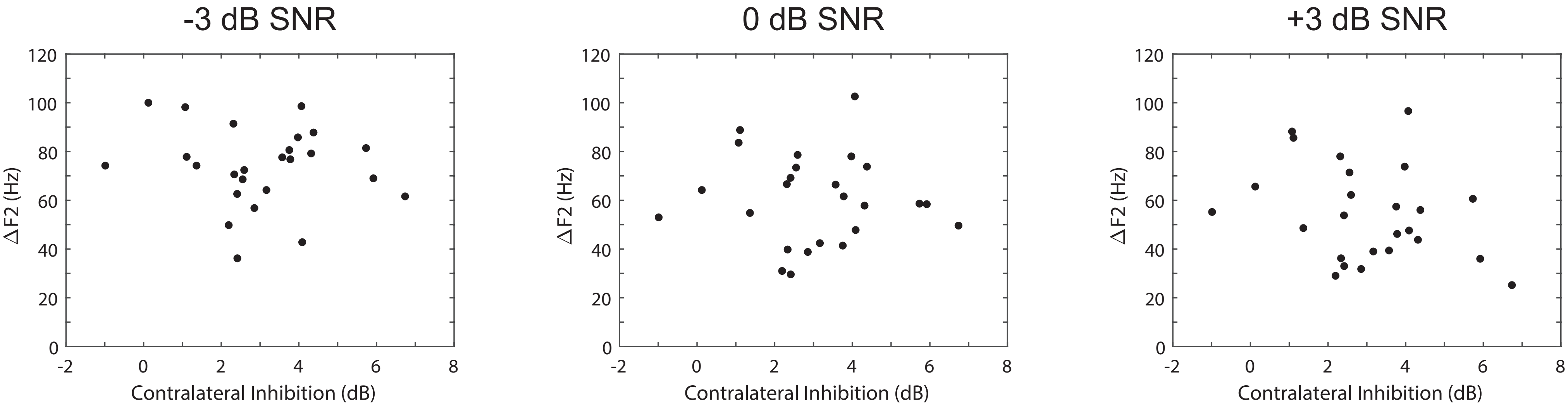


Figure 3


-3 dB SNR
0 dB SNR
+3 dB SNR
ΔF2 (Hz)
0
20
40
60
80
100
120
-2
0
2
4
6
8
Contralateral Inhibition (dB)