Efferent-induced alterations in distortion and reflection otoacoustic emissions in children

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The medial olivocochlear efferent fibers control outer hair cell responses and inhibit the cochlear-amplifier gain. Measuring efferent function is both theoretically and clinically relevant. In humans, medial efferent inhibition can be assayed via otoacoustic emissions (OAEs). OAEs arise by two fundamentally different mechanisms—nonlinear distortion and coherent reflection. Distortion and reflection emissions are typically applied in isolation for studying the efferent inhibition. Such an approach inadvertently assumes that efferent-induced shifts in distortion and reflection emissions provide redundant information. In this study, efferent-induced shifts in distortion and reflection emissions (click-evoked and stimulus frequency OAEs) were measured in the same subjects—5- to 10-yr-old children. Consistent with the OAE generation theory, efferent-induced shifts in distortion and reflection emissions did not correlate, whereas the two reflection emission shifts correlated. This suggests that using either OAE types provides fragmented information on efferent inhibition and highlights the need to use both distortion and reflection emissions for describing efferent effects. © 2018 Acoustical Society of America. <https://doi.org/10.1121/1.5022793>

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I. INTRODUCTION

In humans, the medial efferent system has been conjectured to aid in listening-in-noise, and is diminished in clinical populations such as auditory neuropathy (see Guinan, 2006, 2010, for review; Hood *et al.*, 2003). The medial olivocochlear efferent activity in humans and in laboratory animals is assayed mostly by measuring alterations in otoacoustic emissions (OAEs). OAEs arise by two fundamentally different mechanisms—nonlinear distortion and coherent reflection (Shera and Guinan, 1999). The two types, distortion and reflection emissions, are differentially sensitive to cochlear biophysical properties. For example, distortion emissions depend on the cochlear nonlinearity, and reflection emissions are shaped by cochlear amplifier gain and tuning (Shera, 2004). Recently, Abdala and Kalluri (2017) showed that distortion product otoacoustic emissions (DPOAEs) and stimulus frequency otoacoustic emissions (SFOAEs) have different peak strength and compression features. When DPOAE and SFOAE features were expressed through a joint index (profile) using a two-dimensional plot, the normative relationship was disrupted in mild-to-moderate hearing-impaired ears. Ears with similar hearing thresholds showed differently affected OAE profiles. In addition, hearing impairment occasionally altered either DPOAEs or SFOAEs or one more than the other.

Often, efferent effects are studied by using either distortion-type emissions, e.g., DPOAEs, or reflection-type emissions, e.g., click-evoked otoacoustic emissions (CEOAEs) and SFOAEs (e.g., Backus and Guinan, 2007;

Francis and Guinan, 2010; Goodman *et al.*, 2013; Marshall *et al.*, 2014; Mishra, 2014; Mishra and Dinger, 2016; Wagner *et al.*, 2007). This approach inadvertently ignores that efferent-induced shifts in distortion and reflection emissions provide two kinds of information, and using either may provide fragmented information about efferent modulation. Efferent-induced shifts here refer to alterations in both OAE magnitude and phase.

Conventionally measured DPOAEs consist of both distortion and reflection sources (Kalluri and Shera, 2001; Shera and Guinan, 1999). Efferent inhibition studies that employed inverse time-frequency analysis of DPOAEs considered the dual source OAE model to some extent (Abdala *et al.*, 2009; Deeter *et al.*, 2009; Henin *et al.*, 2011; Mishra and Abdala, 2015). Unfortunately, the commonly used DPOAE stimulus parameters favor distortion emissions, and the extraction of reflection components via inverse fast Fourier transform (IFFT) could be less than perfect (Shaffer and Dhar, 2006); further, the extracted reflection emissions may have a poor signal-to-noise ratio (SNR) as the reflection component is typically ~10 dB below the level of the distortion component (Dewey and Dhar, 2017). Nevertheless, DPOAE studies reveal that efferent stimulation differentially influences distortion and reflection components. Relative to distortion, reflection emission magnitude is reduced more by efferent activation. Likewise, the distortion component undergoes only minimal phase changes, whereas the reflection component undergoes larger phase leads (e.g., Henin *et al.*, 2011).

Characterizing efferent-induced OAE shifts using both distortion- and reflection-emissions in the same subjects will inform whether the various types of OAEs reveal similar or distinct information about efferent modulation. Such

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knowledge is needed to fully understand how the efferent system influences cochlear responses to sounds, and is important for designing experiments for probing the role of efferents in specific perceptual aspects of human hearing. For example, distortion emissions may predict the potential influence of efferents on the cochlear compressive non-linearity because the compression estimates measured by distortion emissions, not reflection emissions, is consistent with the behavioral measures using the growth of forward masking paradigm (Moore *et al.*, 2014). The objective of the present study was to examine whether reflection and distortion emission metrics of efferent inhibition provide complementary information. The working hypothesis was that efferent-induced shifts in the distortion component of DPOAEs and reflection emissions (CEOAEs and SFOAEs) are unrelated due to their different generation mechanisms, whereas efferent-induced shifts in CEOAEs and SFOAEs are related owing to their shared generation—coherent reflections.

II. METHODS

A. Subjects

Thirteen children (8 boys and 5 girls) aged 5 to 10 yrs (mean = 7.4 yrs) participated in this study. We studied children because the relationships between efferent-induced CEOAE and SFOAE shifts have not been demonstrated in children, and also due to our overarching interest to gain a comprehensive understanding of the efferent system during childhood development. All children had hearing thresholds of 15 dB hearing level or lower at octave frequencies 250 through 8000 Hz and had normal tympanograms (peak compensated static acoustic admittance between 0.35 and 1.75 mmho and the tympanometric peak pressure between 0.50 and 100 daPa). All measurements were made in a single test session in a sound-treated booth while the child sat in a reclining chair.

B. OAE measurements

Efferents were stimulated by contralateral broadband noise (CBBN). The measurement goal was to obtain efferent effects using CEOAEs, DPOAEs, and SFOAEs for a one-octave span (707 to 1414 Hz) centered at 1000 Hz for every child. For DPOAEs, this range refers to the f_2 frequencies. This frequency region was chosen because efferent effects are robust in this region, and this region yields desired and comparable SNRs across OAE tests (e.g., Abdala *et al.*, 2013). In addition, CEOAEs and SFOAEs arise by linear coherent reflections and are free from short-delay components at the tested stimulus levels for this frequency region (Lewis and Goodman, 2015; Sisto *et al.*, 2013); short-delay components could potentially complicate a clearer interpretation of efferent effects. One of the challenges is to balance the stimulus levels across OAE procedures. The choice of stimulus level for each test was guided by two factors: optimal level for efferent measurements reported in the literature (Backus and Guinan, 2007; Mishra and Abdala, 2015) and a

level that would yield at least 9 dB SNR for testing children (Mishra and Dinger, 2016).

For DPOAEs and SFOAEs, the depth-compensated ear-simulator calibration was applied (Lee *et al.*, 2012; Mishra and Abdala, 2015). The ER-2 insert earphone frequency response was equalized at the plane of the eardrum individually for each subject by recording the half-wave resonance in the ear canal from 200 to 20 000 Hz, estimating the depth of insertion, and then selecting an appropriate equalization filter to produce approximately a flat frequency response at the tympanic membrane. The in-the-ear calibration method, i.e., a voltage correction, was applied to obtain the target stimulus level in the ear canal for CEOAE measurements. These calibration approaches are effective for the analysis frequencies used in this study (Souza *et al.*, 2014).

Fine-resolution (~ 9 Hz) DPOAEs and SFOAEs were measured using a customized system similar to that described in our past work (Mishra and Abdala, 2015; Mishra and Talmadge, 2017). The stimulus generation and recording of ear canal signals were controlled through the RecordAppX software, developed by Talmadge *et al.* (1999), using a Macintosh computer via a MOTU 828x audio interface (MOTU, Cambridge, MA). The ER-10B+ probe microphone (Etymotic Research, Elk Grove Village, IL) was inserted into the ear canal.

Swept-tone DPOAEs were recorded using stimulus levels of 65 (L_1) and 55 (L_2) dB sound pressure level (SPL) and a constant primary ratio (f_2/f_1) of 1.22. Primaries, f_1 and f_2 , were swept at 5.3 s/octave for a total of 8 sweeps in each condition, with and without CBBN. $2f_1-f_2$ DPOAE level and phase estimates were obtained for the analysis frequencies using a least-squares fit algorithm applied to the average of the eight sweeps (Long *et al.*, 2008). Distortion components were extracted from the composite DPOAEs using an IFFT-based approach implemented in MATLAB (e.g., Abdala *et al.*, 2009; Talmadge *et al.*, 1999). Briefly, DPOAE complex pressure measured in the frequency domain was multiplied by a moving Hanning window (400 Hz width) in overlapping 50 Hz steps. Rectangular time-domain filters were applied to impulse response functions of each window to extract the desired delay components. The filtered windows of data were then transformed back to the frequency domain by fast Fourier transform (FFT) to obtain the level and phase of the distortion (short-delay) and reflection (long-delay) components. Only distortion components were used for describing efferent-induced shifts in DPOAEs because the extracted reflection components, CEOAEs and SFOAEs, share the same generation mechanisms (Shera, 2004; Shera and Guinan, 1999). The amplitude microstructure of the extracted reflection components and SFOAEs are reported to be similar as well (Dewey and Dhar, 2017; Kalluri and Shera, 2001). DPOAEs hereafter in this report refer to the extracted distortion components.

Swept-tone SFOAE recording and analysis were performed using a suppressor technique according to a previous procedure (Mishra and Talmadge, 2017). Probe and suppressor tones were swept at 5.3 s/octave from 500 to 4000 Hz in a two-interval paradigm. The probe and suppressor levels were fixed at 40 and 60 dB SPLs, respectively. The ratio

FIG. 1. (Color online) Representative examples of individual OAE recordings from one child. Solid lines represent OAE levels and dashed lines show noise floor. The abscissa (frequency) is scaled logarithmically.

between the suppressor and probe tone frequency was 1.1 with the suppressor frequency greater than the probe frequency. SFOAEs were estimated from eight probe and eight probe-plus-suppressor swept tones using the least-squares fit method (e.g., Talmadge *et al.*, 1999; Long *et al.*, 2008).

CEOAEs were recorded using the Mimosa HearID system with an ER-10 C probe microphone system similar to our previous study (Mishra and Dinger, 2016). Briefly, 83.3 μ s clicks were presented at 60 dB peak SPL at a rate of 45 Hz, using a linear recording paradigm (Kemp *et al.*, 1986). Responses to 2000 clicks were time-windowed between 2 and 20 ms and were averaged into two alternate buffers. The 2-ms window is appropriate for removing artifacts for the frequency region of interest. Instead of FFT, time-frequency analysis using Stockwell transform was applied to extract CEOAE magnitude and delay for the analysis frequencies at 59 Hz intervals (Mishra and Biswal, 2016; Mishra and Dinger, 2016).

Contralateral broadband noise (100–10 000 Hz) was presented using an ER-2 insert transducer at 60 dB SPL. The CBBN-on and CBBN-off DPOAE conditions were interleaved throughout the test protocol in alternating pairs with 2 s intervals between consecutive sweeps. For SFOAEs, CBBN conditions were interleaved only for the probe sweep, e.g., probe without CBBN, probe with CBBN, and probe-plus-suppressor sweep. In the CBBN-on condition, the noise was presented 1 s prior to the presentation of primary or probe tones. The CBBN conditions were interleaved for the CEOAE as well for every 1000 clicks. The order of OAE tests was randomized and counter-balanced across children. Children did not perform any kind of task during the measurements. The test duration ranged from 60–90 min for each child.

Middle ear muscle reflexes (MEMRs) could potentially confound efferent inhibition measurements. Alterations in the OAE-evoking stimulus level (in linear scale) as measured in the ear canal produced by the CBBN elicitor were calculated to detect MEMRs. The CBBN level that yielded a shift in the stimulus level greater than 1.4% was defined as the MEMR threshold (Abdala *et al.*, 2013; Mishra and Dinger, 2016). MEMR thresholds were greater than 60 dB SPL for all children.

The vector difference between OAE complex pressures, with and without CBBN, used both magnitude and phase information and was normalized by the baseline OAE magnitude for obtaining an efferent inhibition estimate in percent. The values in the analysis frequency range were averaged to obtain a single robust estimate of the efferent effects. For each child, three indices were obtained, Δ CEOAE, Δ DPOAE, and Δ SFOAE, for expressing efferent effects. A larger relative to a smaller Δ OAE represents a robust efferent effect.

III. RESULTS

All children ($n = 13$) completed CEOAE and DPOAE measurements, while SFOAEs were obtained from all but one child ($n = 12$). SFOAE measurements in one child could not be completed due to limited time. Representative examples of individual recordings from a child are shown in Fig. 1. The spectrum for DPOAEs appears to have less periodicity compared to CEOAEs and SFOAEs. The periodic structure for CEOAEs and SFOAEs are broadly similar. Amplitude peaks around 800, 1000, and 1300 Hz can be observed for both CEOAEs and SFOAEs. Clear inhibition of OAE levels was seen at the amplitude peaks, whereas enhancement of OAE levels were observed at certain amplitude minima for CEOAEs (~ 1200 Hz) and SFOAEs (~ 900 Hz). Shifts in peak frequencies due to CBBN were also observed at 1000 Hz for CEOAEs and 800 Hz for SFOAEs. The mean SNRs across subjects for all types of OAEs were comparable (DPOAEs = 18 dB; CEOAEs = 14 dB; SFOAEs = 16 dB). Figure 2 depicts the individual and mean Δ DPOAE, Δ CEOAE, and Δ SFOAE. The mean Δ OAE were 12.70%, 28.64%, and 30.03%, respectively, for DPOAEs, CEOAEs, and SFOAEs.

Figure 3 shows bivariate scatterplots between (a) Δ CEOAE and Δ DPOAE, (b) Δ SFOAE and Δ DPOAE, and (c) Δ SFOAE and Δ CEOAE. Pearson product moment correlation coefficients were computed for examining the relationships between (a) Δ CEOAE and Δ DPOAE, (b) Δ SFOAE and Δ DPOAE, and (c) Δ SFOAE and Δ CEOAE. Dunn–Šidák correction was applied for adjusting the p -value ($p \leq 0.017$).

FIG. 2. (Color online) A bar graph of Δ DPOAE, Δ CEOAE, and Δ SFOAE for each subject (child). Error bars represent standard error of the mean. Δ SFOAE data were missing for subject #3.

There was no significant correlation between Δ DPOAE and Δ CEOAEs ($r = -0.13$, $p = 0.66$), or Δ DPOAE and Δ SFOAEs ($r = 0.02$, $p = 0.95$). Δ CEOAEs and Δ SFOAEs were significantly correlated ($r = 0.68$, $p = 0.016$).

IV. DISCUSSION

The current study investigated efferent-induced shifts in distortion- and reflection-emissions in the same subjects. Efferent-induced shifts in distortion OAEs were not related to those in reflection OAEs (CEOAEs or SFOAEs). In contrast, CEOAE- and SFOAE-shifts revealed a modest, positive correlation. This suggests that distortion (DPOAEs) and reflection (CEOAEs or SFOAEs) source metrics of efferent function provide non-redundant information, whereas CEOAEs and SFOAEs yield similar information about the efferent inhibition of cochlear mechanical responses. This interpretation is consistent with the theory of OAE generation which suggests that distortion and reflection emissions arise by two fundamentally different mechanisms, and CEOAEs and SFOAEs are thought to primarily result from coherent reflections for the stimulus levels tested in this study (Shera and Guinan, 1999). One could argue that the lack of a relationship between DPOAE- and SFOAE-shifts

could be due to the use of different stimulus levels for the two tests. However, the amount of frequency shift in DPOAEs due to efferent stimulation does not vary systematically with increases in the L_2 primary level (Henin *et al.*, 2011). We selected the L_2 level as 55 dB SPL to obtain acceptable SNRs across children and to get similar SNRs across OAE types. Additionally, the distortion component growth is known to be linear at the tested L_2 level for 1000 Hz (Mauermann and Kollmeier, 2004). Measuring efferent effects in linear growth regions for both DPOAEs and SFOAEs likely shielded potential stimulus-related effects.

Efferent stimulation differentially altered distortion- and reflection-emissions with a relatively more pronounced effect on reflection OAEs consistent with past work in adults and newborns (Abdala *et al.*, 2009, 2013; Mishra and Abdala, 2015). Current findings related to reflection emissions are consistent with previous studies (Francis and Guinan, 2010; Marshall *et al.*, 2014). Marshall *et al.* (2014) reported similar relationships between Δ CEOAEs and Δ SFOAEs in adults and Francis and Guinan (2010) showed the similarity between efferent-induced shifts in CEOAE- and SFOAE-delays. We extended these findings to children. The mean Δ SFOAE (30.03%) was comparable with previous studies in adults (Δ SFOAE mean = 36.6%, Backus and Guinan, 2007; Δ SFOAE mean = 29%, Marshall *et al.*, 2014), whereas the mean Δ CEOAE was slightly lower than that reported by Marshall *et al.* (2014), potentially due to the use of a relatively lower click level and/or the use of pediatric subjects in the current study.

Although we studied children, the main findings—inter-relationships between various OAE-shifts—should be generalizable to adults because efferent effects are considered to be mature at full-term birth (Abdala *et al.*, 2013). These findings have high significance for designing tests to assay efferent inhibition. Typically, CEOAEs, DPOAEs, and SFOAEs are applied in isolation for studying efferent mechanisms. The present study underscores the importance of applying both distortion- and reflection-emissions for characterizing efferent inhibition. We applied a commonly used IFFT approach to extract distortion components from DPOAEs. Alternatively, the window of the least-squared-fit analysis

FIG. 3. Bivariate scatterplots depicting the relationship between various efferent-induced shifts (a) CEOAEs and DPOAEs, (b) SFOAEs and DPOAEs, and (c) SFOAEs and CEOAEs (the line represents the least-squared-fit; Δ CEOAE = $0.5 \times \Delta$ SFOAE + 14.9).

and recording parameters can be adjusted to obtain predominantly distortion components (Abdala *et al.*, 2015). While both CEOAEs and SFOAEs yielded similar results, SFOAEs are preferred reflection-emissions for assaying efferent inhibition because tones used to evoke SFOAEs relative to clicks are less potent elicitors of MEMRs (Guinan *et al.*, 2003).

Applying both distortion and reflection emissions for probing efferent effects may reveal subtle differences in efferent inhibition between subjects. For example, a reduced DPOAE-shift may indicate the lack of an adequate efferent control on the cochlear compression, whereas a reduced SFOAE-shift may suggest a limited efferent modulation of the sensitivity and tuning. Similarly, DPOAE- and SFOAE-shifts may elucidate the role of efferents in different perceptual processes, such as loudness growth and frequency selectivity, respectively. Conversely, it may be intuitive to integrate both DPOAE- and SFOAE-shifts for relating efferent effects with speech perception in noise, or for studying the effect of certain clinical conditions such as auditory processing disorders. In cases where detectability of efferent effects is a concern, SFOAE- or CEOAE-shifts may be used as a metric for efferent strength because they are larger than DPOAE-shifts. Nevertheless, such speculations need experimental verification.

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Abdala, C., and Kalluri, R. (2017). "Towards a joint reflection-distortion otoacoustic emission profile: Results in normal and impaired ears," *J. Acoust. Soc. Am.* **142**, 812–824.

Abdala, C., Luo, P., and Shera, C. A. (2015). "Optimizing swept-tone protocols for recording distortion-product otoacoustic emissions in adults and newborns," *J. Acoust. Soc. Am.* **138**, 3785–3799.

Abdala, C., Mishra, S., and Garinis, A. (2013). "Maturation of the human medial efferent reflex revisited," *J. Acoust. Soc. Am.* **133**, 938–950.

Abdala, C., Mishra, S. K., and Williams, T. L. (2009). "Considering distortion product otoacoustic emission fine structure in measurements of the medial olivocochlear reflex," *J. Acoust. Soc. Am.* **125**, 1584–1594.

Backus, B. C., and Guinan, J. J. (2007). "Measurement of the distribution of medial olivocochlear acoustic reflex strengths across normal-hearing individuals via otoacoustic emissions," *J. Assoc. Res. Otolaryngol.* **8**, 484–496.

Deeter, R., Abel, R., Calandruccio, L., and Dhar, S. (2009). "Contralateral acoustic stimulation alters the magnitude and phase of distortion product otoacoustic emissions," *J. Acoust. Soc. Am.* **126**, 2413–2424.

Dewey, J. B., and Dhar, S. (2017). "Profiles of stimulus-frequency otoacoustic emissions from 0.5 to 20 kHz in humans," *J. Assoc. Res. Otolaryngol.* **18**, 89–110.

Francis, N., and Guinan, J. J. (2010). "Acoustic stimulation of human medial olivocochlear efferents reduces stimulus frequency- and click-evoked otoacoustic emission delays: Implications for cochlear filter bandwidths," *Hear Res.* **267**, 36–45.

Goodman, S. S., Mertes, I. B., Lewis, J. D., and Weissbeck, D. K. (2013). "Medial olivocochlear-induced transient-evoked otoacoustic emission amplitude shifts in individual subjects," *J. Assoc. Res. Otolaryngol.* **14**, 829–842.

Guinan, J. J. (2006). "Olivocochlear efferents: Anatomy, physiology, function, and the measurement of efferent effects in humans," *Ear Hear.* **27**, 589–607.

Guinan, J. J. (2010). "Cochlear efferent innervation and function," *Curr. Opin. Otolaryngol. Head Neck Surg.* **18**, 447–453.

Guinan, J. J., Backus, B. C., Lilaonitkul, W., and Aharonson, V. (2003). "Medial olivocochlear efferent reflex in humans: Otoacoustic emission (OAE) measurement issues and the advantages of stimulus frequency OAEs," *J. Assoc. Res. Otolaryngol.* **4**, 521–540.

Henin, S., Thompson, S., Abdelrazeq, S., and Long, G. R. (2011). "Changes in amplitude and phase of distortion-product otoacoustic emission fine-structure and separated components during efferent activation," *J. Acoust. Soc. Am.* **129**, 2068–2079.

Hood, L. J., Berlin, C. I., Bordelon, J., and Rose, K. (2003). "Patients with auditory neuropathy/dys-synchrony lack efferent suppression of transient evoked otoacoustic emissions," *J. Am. Acad. Audiol.* **14**, 302–313.

Kalluri, R., and Shera, C. A. (2001). "Distortion-product source unmixing: A test of the two-mechanism model for DPOAE generation," *J. Acoust. Soc. Am.* **109**, 622–637.

Kemp, D. T., Bray, P., Alexander, L., and Brown, A. M. (1986). "Acoustic emission cochleography—practical aspects," *Scand. Audiol. Suppl.* **25**, 71–95.

Lee, J., Dhar, S., Abel, R., Banakis, R., Grolley, E., Lee, J., Zecker, S., and Siegel, J. (2012). "Behavioral hearing thresholds between 0125 and 20 kHz using depth-compensated ear simulator calibration," *Ear Hear.* **33**, 315–329.

Lewis, J. D., and Goodman, S. S. (2015). "Basal contributions to short-latency transient-evoked otoacoustic emission components," *J. Assoc. Res. Otolaryngol.* **16**, 29–45.

Long, G. R., Talmadge, C. L., and Lee, J. (2008). "Measuring distortion product otoacoustic emissions using continuously sweeping primaries," *J. Acoust. Soc. Am.* **124**, 1613–1626.

Marshall, L., Lapsley Miller, J. A., Guinan, J. J., Shera, C. A., Reed, C. M., Perez, Z. D., Delhorne, L. A., and Boege, P. (2014). "Otoacoustic-emission-based medial-olivocochlear reflex assays for humans," *J. Acoust. Soc. Am.* **136**, 2697–2713.

Mauermann, M., and Kollmeier, B. (2004). "Distortion product otoacoustic emission (DPOAE) input/output functions and the influence of the second DPOAE source," *J. Acoust. Soc. Am.* **116**, 2199–2212.

Mishra, S. K. (2014). "Attentional modulation of medial olivocochlear inhibition: Evidence for immaturity in children," *Hear. Res.* **318**, 31–36.

Mishra, S. K., and Abdala, C. (2015). "Stability of the medial olivocochlear reflex as measured by distortion product otoacoustic emissions," *J. Speech, Lang. Hear. Res.* **58**, 122–134.

Mishra, S. K., and Biswal, M. (2016). "Time-frequency decomposition of click evoked otoacoustic emissions in children," *Hear. Res.* **335**, 161–178.

Mishra, S. K., and Dinger, Z. (2016). "Influence of medial olivocochlear efferents on the sharpness of cochlear tuning estimates in children," *J. Acoust. Soc. Am.* **140**, 1060–1071.

Mishra, S. K., and Talmadge, C. L. (2017). "Sweep-tone evoked stimulus frequency otoacoustic emissions in humans: Development of a noise-rejection algorithm and normative features," *Hear. Res.* (published online).

Moore, T. M., Hood, L. J., and Hornsby, B. W. Y. (2014). "Estimates of cochlear compression using distortion product otoacoustic emissions and growth of forward masking," *Ear Hear.* **35**, 711–714.

Shaffer, L. A., and Dhar, S. (2006). "DPOAE component estimates and their relationship to hearing thresholds," *J. Am. Acad. Audiol.* **17**, 279–292.

Shera, C. A. (2004). "Mechanisms of mammalian otoacoustic emission and their implications for the clinical utility of otoacoustic emissions," *Ear Hear.* **25**, 86–97.

Shera, C. A., and Guinan, J. J. (1999). "Evoked otoacoustic emissions arise by two fundamentally different mechanisms: A taxonomy for mammalian OAEs," *J. Acoust. Soc. Am.* **105**, 782–798.

Sisto, R., Sanjust, F., and Moleti, A. (2013). "Input/output functions of different-latency components of transient-evoked and stimulus-frequency otoacoustic emissions," *J. Acoust. Soc. Am.* **133**, 2240–2253.

Souza, N. N., Dhar, S., Neely, S. T., and Siegel, J. H. (2014). "Comparison of nine methods to estimate ear-canal stimulus levels," *J. Acoust. Soc. Am.* **136**, 1768–1787.

Talmadge, C. L., Long, G. R., Tubis, A., Dhar, S., and Glenis, L. R. (1999). "Experimental confirmation of the two-source interference model for the fine structure of distortion product otoacoustic emissions," *J. Acoust. Soc. Am.* **105**, 275–292.

Wagner, W., Heppelmann, G., Müller, J., Janssen, T., and Zenner, H.-P. (2007). "Olivocochlear reflex effect on human distortion product otoacoustic emissions is largest at frequencies with distinct fine structure dips," *Hear. Res.* **223**, 83–92.