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Human medial efferent activity elicited by dynamic versus static contralateral noises

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11 **Abstract**

12 The medial olivocochlear reflex (MOCR) modifies cochlear amplifier function to improve

13 encoding of signals in static noise, but conflicting results have been reported regarding how the

14 MOCR responds to dynamic, temporally-complex noises. The current study utilized three

15 MOCR elicitors with identical spectral content but different temporal properties: broadband

16 noise, amplitude-modulated noise, and speech envelope-modulated noise. MOCR activity was

17 assessed using contralateral inhibition of transient-evoked otoacoustic emissions in 27 normal-

18 hearing young adults. Elicitors were presented contralaterally at two intensities of 50 and

19 60 dB SPL. Magnitude and growth of contralateral inhibition with increasing elicitor intensity

20 were compared across the three elicitor types. Results revealed that contralateral inhibition was

21 significantly larger at the elicitor intensity of 60 dB SPL than at 50 dB SPL, but there were no

22 significant differences in the magnitude and growth of inhibition across the three elicitors,

23 contrary to hypothesis. These results suggest that the MOCR responds similarly to both static

24 and dynamic noise.

25

26 **Keywords**

29

30 **Abbreviations**

31 AM, amplitude-modulated; BBN, broadband noise; CAS, contralateral acoustic stimulation; EM,

32 envelope-modulated; MEMR, middle-ear muscle reflex; MOC, medial olivocochlear; MOCR,

33 medial olivocochlear reflex; OAE, otoacoustic emission; pSPL, peak sound pressure level;

34   SSOAE, synchronized spontaneous otoacoustic emission; TEOAE, transient-evoked otoacoustic

35   emission

1. Introduction

The medial olivocochlear (MOC) efferent system modulates cochlear amplifier function through descending fibers that project from the brainstem to the outer hair cells (reviewed in Guinan, 2006). Afferent stimulation of the MOC triggers a reflex (MOC reflex, or MOCR) which improves auditory nerve encoding of transient sounds in background noise by reducing the neural response to the noise (Winslow and Sachs, 1987; Kawase et al., 1993). The MOCR appears to contribute to normal-hearing listeners' ability to understand speech in noisy situations (e.g., Giraud et al., 1997; Mertes et al., 2017). The MOCR is typically assessed non-invasively in humans using transient-evoked otoacoustic emissions (TEOAEs), which are measurable sounds generated in response to brief stimuli that are a byproduct of the cochlear amplification process (Kemp, 1978; Brownell, 1990). When measuring TEOAEs in one ear, presentation of contralateral sound activates the contralateral MOC pathway, decreasing cochlear amplifier gain and reducing TEOAE amplitude (Collet et al., 1990; Berlin et al., 1993). This process is referred to as contralateral inhibition, and larger inhibition is interpreted as a stronger MOCR (Backus and Guinan, 2007).

The MOCR is responsive to a variety of sounds, including pure tones, clicks, tone bursts, and noise (e.g., Veuillet et al., 1991; Berlin et al., 1993; Guinan et al., 2003). The magnitude of contralateral inhibition increases with increasing level and bandwidth of the contralateral stimulus, with static white noise yielding the largest inhibition (Maison et al., 2000; Velenovsky and Glattke, 2002; Guinan et al., 2003; Lilaonitkul and Guinan, 2009). Static white noise therefore has been used as the contralateral stimulus in nearly all studies of contralateral inhibition in humans. Despite the usefulness of using static white noise to study contralateral inhibition in laboratory settings, it is unclear how more dynamic, temporally-complex sounds

59 activate the MOCR. If the MOCR responds differently to dynamic versus static noises, then

60 measurements of contralateral inhibition using static white noise may not reflect the behavior of

61 the MOCR in the presence of background noises that humans often encounter, such as multi-

62 talker babble.

63   A small number of studies have examined contralateral inhibition using dynamic

64 contralateral sounds, but results have been equivocal. One group found that amplitude-

65 modulated (AM) sinusoids and AM broadband noise (BBN) yielded larger contralateral

66 inhibition relative to unmodulated sinusoids and unmodulated BBN (Maison et al., 1997; 1999;

67 2001), consistent with the modulation transfer function measured in individual MOC neurons of

68 the guinea pig (Gummer et al., 1988). However, Boothalingam et al. (2014) found a trend of

69 reduced contralateral inhibition of otoacoustic emissions (OAEs) elicited with single-tone stimuli

70 (stimulus frequency OAEs) when the tones were AM versus unmodulated. No significant

71 differences were seen in contralateral inhibition when elicited by a babble noise relative to white

72 noise (Timpe-Syverson and Decker, 1999; Papsin et al., 2014), but these studies did not report

73 sufficient controls for middle-ear muscle reflex activation which could interfere with the

74 interpretation of results (Goodman et al., 2013) and the click stimulus rate of 50/s may have

75 elicited the ipsilateral MOCR (Boothalingam and Purcell, 2015). A recent paper examined the

76 effect of a variety of contralateral noises on contralateral inhibition (Kalaiah et al., 2017). The

77 noises included BBN, AM noise (4, 50, and 100 Hz modulation frequencies), multi-talker babble

78 (two, four, and six talkers), and environmental (traffic and cafeteria) noises. Results showed that

79 the multi-talker babble and traffic noises elicited significantly lower contralateral inhibition than

80 BBN. The authors concluded that multi-talker babble noise is a less efficient activator of the

81 MOCR than other noises, which could have implications for how the MOCR is activated in real-

82 world listening situations. However, there were differences in the spectral content of the noises

83 (see their Fig. 2), so it cannot be determined if the differences in MOCR activation were due to

84 differences in the spectral and/or temporal content of the noises.

85   The primary purpose of the current study was to compare the magnitude of contralateral

86 inhibition elicited by three contralateral noises that varied in their temporal characteristics while

87 holding the spectral content the same. Static BBN and two dynamic noises (AM BBN and BBN

88 modulated by the envelope of multi-talker babble) were utilized. It was hypothesized that BBN

89 would elicit significantly larger contralateral inhibition than the dynamic noises because the lack

90 of low-amplitude dips in the static noise would ensure sustained activation of the MOCR

91 (Boothalingam et al., 2014). The growth of contralateral inhibition for the three noise elicitors

92 was also explored to determine if the MOCR responds differentially across elicitor intensity level

93 depending upon the temporal characteristics of the elicitor.

94

95 **2. Material and methods**

96 *2.1. Participants*

97   A total of 27 participants (20 females) participated. Participant ages ranged from 18 to 40

98 years [mean = 23.5 years, standard deviation (SD) = 5.9]. Screening procedures included a case

99 history and audiologic screening. Eligible participants were required to have a self-reported

100 negative history of the following: hearing difficulties, significant noise exposure within the past

101 6 months, tinnitus of a severe and/or bothersome nature, use of ototoxic medication, vertigo, and

102 chronic middle ear pathology. Participants were also required to be right handed to avoid

103 confounds of handedness effects on contralateral inhibition (Khalfa et al., 1998).

104   Audiologic inclusion criteria consisted of the following: an unremarkable otoscopic

105   examination bilaterally, normal 226-Hz tympanograms bilaterally (tympanometric peak pressure

106   between -100 to +50 daPa, static acoustic admittance between 0.2 to 1.8 mmho, and equivalent

107   ear canal volume from 0.6 to 2.5 cc), pure-tone air-conduction thresholds ≤20 dB HL at octave

108   frequencies from 250 to 8000 Hz bilaterally, and measurable TEOAEs in the right ear. The

109   TEOAE screening measurement consisted of collecting 1250 sweeps in response to 40.96-µs

110   clicks presented at 65 dB peak sound pressure level (pSPL) at a rate of 19.53/s using equipment

111   described in Sec. 2.2. Mean TEOAE waveforms were bandpass filtered from 1000 to 2000 Hz.

112   Participants passed the TEOAE screening if the time-domain signal-to-noise ratio (SNR) was >6

113   dB and the whole-waveform reproducibility (Kemp et al., 1990) was >70%.

114   The study protocol was approved by the Institutional Review Board of the University of

115   Illinois at Urbana-Champaign. Written informed consent was obtained by all participants prior to

116   their enrollment in the study. All participants received monetary compensation for their

117   participation.

118

119   *2.2. Equipment*

120   Participants were seated in a comfortable recliner inside a 200 sq. ft. single-walled sound-

121   treated booth with 8-in thick walls (Tracoustics, Inc., Austin, TX). To further reduce external

122   noise from entering the sound booth, the experimenters were situated in a separate room with the

123   door closed. The experimenters monitored participants during the experiment via a camcorder

124   and intercom.

125   Audiometric screenings were conducted using an AudioStar Pro audiometer (Grason-

126   Stadler, Inc., Eden Prarie, MN) and a Titan tympanometer (Interacoustics, Middelfart, Denmark).

127   Contralateral inhibition testing was conducted using a WS-4 workstation [Tucker-Davis

128   Technologies (TDT), Alachua, FL] and an RZ6 auditory processor (TDT) running custom

129   software written in MATLAB (ver. R2017a, The Mathworks, Inc., Natick, MA) and RPvdsEx

130   (TDT). Stimuli were routed from the RZ6 to two resistors (1/8 W, 22 Ω) that were placed in

131   series with a pair of ER-2 insert earphones (Etymōtic Research, Elk Grove Village, IL). The

132   acoustic tubing of the right insert earphone was connected to an ER-10B+ probe microphone

133   system (Etymōtic Research) with the preamplifier gain set to +40 dB. The signal recorded by the

134   microphone was routed to the input of the RZ6, sampled at 24414.06 Hz (the default sampling

135   rate of the processor), and streamed to the workstation hard disk.

136   Offline analyses of TEOAE waveforms were performed using a combination of custom

137   MATLAB code and the MATLAB Signal Processing Toolbox (ver. 11.1, The Mathworks, Inc.).

138   Statistical analyses were conducted using SPSS Statistics (version 24.0.0.0, IBM Corp., Armonk,

139   NY).

140

141   *2.3. Contralateral inhibition measurement*

142   Stimulus and recording parameters were adapted from those described in Mertes et al.

143   (2017). Contralateral inhibition measurement consisted of obtaining TEOAEs with and without

144   the three contralateral elicitors described in this section. TEOAEs were elicited using clicks

145   generated by the RZ6 processor at the default sampling rate of 24414.06 Hz. Click stimuli were

146   40.96 µs in duration and were presented at a level of 65 dB pSPL and at a rate of 19.53/s. The

147   stimulus level was selected to ensure robust elicitation of TEOAEs in all participants (Mertes et

148   al., 2017), while the rate was selected to reduce potential elicitation of both the ipsilateral MOCR

149   and the middle-ear muscle reflex (MEMR) by the click stimuli (Boothalingam and Purcell,

150 2015). The activation of either of these reflexes can confound the interpretation of the

151 contralateral inhibition results and are thus desirable to avoid (Guinan et al., 2003; Boothalingam

152 and Purcell, 2015).

153   Three noise stimuli served as contralateral elicitors of the MOCR (referred to hereafter as

154 *elicitor types*): 1) broadband noise (*BBN*) consisting of Gaussian noise generated by the RZ6

155 processor with a nominal bandwidth of 0 to 12207 Hz; 2) amplitude-modulated (*AM*) BBN,

156 consisting of the BBN from elicitor 1 that was amplitude-modulated at a rate of 100 Hz and at a

157 modulation depth of 100%; 3) envelope-modulated (*EM*) BBN, consisting of the BBN from

158 elicitor 1 that was modulated by the envelope of a four-talker babble stimulus (Lilly et al., 2011),

159 where the envelope was obtained by convolving the absolute value of the babble stimulus with a

160 7.2-ms rectangular window (Brungart et al., 2001). The AM elicitor was utilized to determine the

161 replicability of the results of Maison et al. (1999). EM noise was utilized to determine if the

162 MOCR is responsive to the aperiodic amplitude fluctuations that are present in multi-talker

163 babble. The first 1000 ms of each elicitor waveform are shown in Figure 1. Waveforms were

164 ramped on and off with 50-ms cosine-squared ramps. Elicitor waveforms were scaled to have an

165 equal root-mean-square (RMS) amplitude and the SPLs were calibrated in a 2-cc coupler.

166   Contralateral inhibition was assessed by interleaving measurements of TEOAEs without

167 and with contralateral acoustic stimulation (referred to hereafter as *CAS-* and *CAS+*,

168 respectively). A single interleave consisted of 8 s in CAS- (clicks only), followed by 500 ms of

169 elicitor presentation to allow for the onset of the MOCR (Backus and Guinan, 2006), followed

170 by 8 s in CAS+ (clicks and elicitor), and finally 500 ms of silence to allow for the offset of the

171 MOCR prior to the next presentation of CAS- (Backus and Guinan, 2006). Each elicitor

172 waveform was 4.8 min in duration. To avoid presenting frozen noise, each interleave in CAS+

173   involved presenting a random 8-s segment drawn from the total elicitor waveform. The

174   waveforms were then ramped on and off with a 10-ms cosine-squared window. A total of 1250

175   sweeps in each of the CAS- and CAS+ conditions (i.e., eight interleaves of CAS- and CAS+

176   conditions) were obtained for a single measurement of contralateral inhibition. Recorded

177   waveforms were high pass filtered with a second-order Butterworth filter with a cutoff frequency

178   of 500 Hz via the RPvdsEx software, then streamed to disk for offline analysis.

179   For each contralateral noise stimulus, a measurement of contralateral inhibition was

180   obtained by presenting the noise at 50 or 60 dB SPL (A-weighted RMS) (hereafter referred to as

181   *elicitor intensity*). Therefore, there were a total of six conditions (3 elicitor types × 2 elicitor

182   intensities) for each participant. The presentation order of conditions was randomized for each

183   participant.[1] Prior to the recording at each condition, the click stimulus levels were calibrated in-

184   situ and were adjusted until the pSPL of the click was within ±0.25 dB of the target level.

185   Participants were instructed to remain as still and quiet as possible during the

186   contralateral inhibition measurements. Participants watched a closed-captioned silent video of

187   their choice on an iPad Air 2 tablet (Apple, Cupertino, CA). After each measurement, there was a

188   brief intermission while the experimenter prepared the software for the next recording.

189   Participants were provided with a short break between measurements as needed. The earphones

190   were kept inserted between measurements.

191

192   *2.4. MEMR analysis*

193   Prior to analyzing the contralateral inhibition results, it was critical to assess the presence

194   of MEMR activation. We implemented a check for the presence of MEMR based on recent

195   reports (Abdala et al., 2013; Boothalingam and Purcell, 2015; Mertes and Leek, 2016), where

196 changes in stimulus amplitude measured in the ear canal were compared between CAS- and

197 CAS+. The rationale for this method is that activation of the MEMR can alter middle ear

198 impedance and thus alter the stimulus amplitude measured in the ear canal. The stimulus

199 waveforms recorded in the ear canal were time-windowed to isolate the stimulus peak. Probable

200 activation of the MEMR was considered present when the mean peak amplitude in CAS+ was

201 ≥0.12 dB larger relative to CAS-. The presence of MEMR was assessed in all elicitor type ×

202 elicitor intensity conditions. However, no participants demonstrated probable MEMR activation.

203

204 *2.5. Contralateral inhibition analysis*

205 For each contralateral inhibition measurement, the waveforms were split into two

206 matrices comprising TEOAEs obtained in CAS- and CAS+. Both matrices were reshaped into

207 1250 sweeps, where time zero was set to the time location corresponding to the stimulus peak.

208 TEOAE waveforms were time windowed from 8 to 18 ms (Hood et al., 1996) and ramped on and

209 off with 1-ms cosine-squared ramps so that the waveforms were at full amplitude from 8 to

210 18 ms. Waveforms were then bandpass filtered with a Hann window-based filter (passband =

211 891 to 2245 Hz, filter order = 128). Artifacts were rejected post hoc by excluding any sweep

212 having an RMS amplitude that fall outside 1.5 times the interquartile range of the distribution of

213 RMS amplitudes across all sweeps (Goodman et al., 2009).

214 Quantification of contralateral inhibition was performed using methods based on Mertes

215 and Leek (2016). Estimates of the TEOAE signal and noise floor amplitudes were first computed

216 by putting odd- and even-numbered sweeps into sub-buffers *A* and *B*, respectively. The TEOAE

217 signal waveform was obtained as $\frac{(A+B)}{2}$ and the TEOAE noise floor waveform was computed as

218 $\frac{(A-B)}{2}$ (Prieve et al., 1993). A mean signal waveform and mean noise floor waveform were

11

219 obtained for both CAS- and CAS+. When measured in an IEC711 coupler, the RMS SNR was

220 <6 dB, indicating sufficiently low system distortion. Figure 2 shows an example of mean

221 TEOAE waveforms in CAS- and CAS+ for one representative participant. The SNR of the mean

222 waveform in CAS- was required to be >6 dB to be included in the contralateral inhibition

223 analysis. Contralateral inhibition was computed as the difference in RMS amplitude between the

224 mean TEOAE waveforms in CAS+ and CAS-, expressed in decibels. Positive values indicated

225 that TEOAE magnitude decreased in CAS+, which was the expected effect. Larger positive

226 values were interpreted as stronger MOCR activity (Backus and Guinan, 2007).

227 We also examined contralateral inhibition within 2-ms time windows to examine

228 differences in contralateral inhibition across different times among the three elicitor types and

229 two elicitor intensities. Due to the frequency dispersion of TEOAEs across time, later analysis

230 windows represent MOCR effects on lower frequencies (Berlin et al., 1993). Velenovsky and

231 Glattke (2002) found that when comparing different contralateral MOCR elicitors, significant

232 differences were seen in the amount of contralateral inhibition across these time windows.

233 Therefore, it was of interest to determine if a similar result would be seen across the different

234 noise elicitors used in the current study. Contralateral inhibition was calculated in the same way

235 as described above in Sec. 2.5, except rather than computing across the duration 8 to 18 ms, five

236 non-overlapping analysis windows were utilized: 8–10, 10–12, 12–14, 14–16, and 16–18 ms.

237

3. Results

3.1 Magnitude of contralateral inhibition

240 TEOAE signal and noise floor amplitudes across elicitor type × elicitor intensity

241 conditions are shown in Fig. 3. As expected, TEOAE amplitudes in CAS- appeared stable and

242 TEOAE amplitudes decreased in CAS+ across all conditions. Additionally, noise floors appeared

243 stable across conditions and were comparable between CAS- and CAS+. Mean SNRs for the 50

244 dB SPL elicitor intensity were 19.34 dB for CAS- and 17.30 dB for CAS+ (collapsed across

245 elicitor). Mean SNRs for the 60 dB SPL elicitor intensity were 19.38 dB for CAS- and 15.59 dB

246 for CAS+ (collapsed across elicitor). TEOAE signal amplitudes were not normally distributed at

247 all elicitor type × elicitor intensity conditions as assessed by Shapiro-Wilk tests of normality ($p <$

248 0.05), therefore the mean TEOAE signal amplitudes across conditions were not analyzed with

249 repeated measures analyses of variance (ANOVA).

250 However, the primary outcome of interest was contralateral inhibition (i.e., the difference

251 in TEOAE amplitude between CAS- and CAS+). Mean contralateral inhibition values are shown

252 in Fig. 4. A two-way repeated measures ANOVA was run to determine the effect of the factors

253 of elicitor type (BBN, AM, and EM) and elicitor intensity (50 and 60 dB SPL) on contralateral

254 inhibition. Outlier detection was utilized by examining the studentized residuals, which are

255 residuals divided by an estimate of the standard error. No outliers were present, as evidenced by

256 studentized residuals that did not exceed ±3 standard deviations. Contralateral inhibition was

257 normally distributed as assessed by a Shapiro-Wilk test of normality on the studentized residuals

258 ($p > 0.05$). Mauchly's test of sphericity indicated that the assumption of sphericity was met for

259 the interaction between elicitor type and elicitor intensity, the main effect of elicitor type, and the

260 main effect of elicitor intensity ($p > 0.05$ in all cases). There was no significant interaction

261 between elicitor type and elicitor intensity, $F(2,52) = 1.560$, $p = 0.220.$, $\chi^2(2) = 3.155$, $p = 0.207$.

262 The main effect of elicitor type was not statistically significant, $F(2,52) = 2.940$, $p = 0.062$. The

263 main effect of elicitor intensity showed that there was a statistically significant difference in

264 contralateral inhibition between elicitor intensities, $F(1,26) = 34.925$, $p < 0.0005$, partial $\eta^2 =$

265 0.573. Post hoc analysis revealed that contralateral inhibition significantly increased from an

266 elicitor intensity of 50 dB SPL to 60 dB SPL (1.477 dB, 95% CI = 0.963 to 1.990, $p < 0.0005$).

267   Mean results of the analysis in 2-ms time windows are plotted in Fig. 5. The left and right

268 panels display the results obtained for elicitor intensities of 50 and 60 dB SPL, respectively. Two

269 outliers were present, as evidenced by studentized residuals that exceeded +3 standard

270 deviations. Additionally, contralateral inhibition was not normally distributed at all analysis

271 window × elicitor type × elicitor intensity conditions, as assessed by Shapiro-Wilk tests of

272 normality on the studentized residuals ($p < 0.05$). Therefore, a three-way repeated measures

273 ANOVA was not performed. Rather, the data were analyzed qualitatively.

274   At a given analysis window, mean contralateral inhibition was larger for an elicitor

275 intensity of 60 dB SPL compared to 50 dB SPL, which was expected given the results shown in

276 Fig. 4. At both elicitor intensities, contralateral inhibition was smallest at 8–10 ms. For a given

277 elicitor type, fluctuations in contralateral inhibition can be seen with increasing analysis

278 window. Across analysis windows, differences in contralateral inhibition among the three elicitor

279 types can be seen – no clear pattern emerged for an elicitor intensity of 50 dB SPL but BBN

280 tended to exhibit larger contralateral inhibition relative to the other elicitor types at 60 dB SPL.

281

282 *3.2 Inhibition versus enhancement of TEOAE amplitude*

283   It was also of interest to examine the distribution of contralateral inhibition values at each

284 elicitor type × elicitor intensity condition. Box and whisker plots of contralateral inhibition are

285 displayed in Fig. 6. The majority of contralateral inhibition values were positive, indicating that

286 TEOAE amplitude decreased in CAS+ as expected. However, there were instances of negative

287 inhibition values at each elicitor type × elicitor intensity condition (ranging from 6 to 7 instances

14

288   at 50 dB SPL and from 3 to 4 instances at 60 dB SPL). These enhancements in TEOAE

289   amplitude could not be explained by MEMR activation.

290   We examined the potential contribution of synchronized spontaneous OAEs (SSOAEs) to

291   these enhancements. SSOAEs are outer hair cell responses that become entrained to click stimuli

292   and persist for longer than TEOAEs (Prieve and Falter, 1995). Participants with SSOAEs may

293   exhibit phase cancellations between SSOAEs and TEOAEs in the absence of MOCR activation.

294   If the MOCR differentially inhibited SSOAEs versus TEOAEs, there may be an increase in the

295   measured TEOAE amplitude (S. Boothalingam, personal communication). Such an effect would

296   be similar to the well-established differential impact of MOCR activation on the distortion versus

297   reflection components of distortion-product otoacoustic emissions, which can result in increases

298   in OAE amplitude when the MOCR is activated (e.g., Abdala et al., 2009).

299   SSOAEs were extracted using the same methods described in Sec. 2.5 but using a time

300   window from 36 to 44 ms post-stimulus onset, where no TEOAEs were expected to occur. To

301   detect the presence of SSOAEs, a 1024-point FFT was computed on the mean waveform in the

302   SSOAE window and was compared to the FFT computed on the mean waveform in the TEOAE

303   window (8 to 18 ms). SSOAEs were considered present if the SNR in the SSOAE window was

304   >6 dB. Two case examples of participants with SSOAEs are shown in Fig. 7. Results are shown

305   for AM noise presented at 50 dB SPL, in which 7 participants showed enhancements with CAS+.

306   The top row shows results from a participant with enhancements and the bottom row shows

307   results from a participant with inhibition. The participant shown in the top row demonstrated

308   enhancements in both TEOAE and SSOAE amplitude in CAS+. Visual inspection of data

309   showed that of the seven participants demonstrating enhancements in TEOAE amplitude, four of

310   them also demonstrated SSOAEs that also were enhanced with CAS+ (the remaining three did

311   not have SSOAEs). The participant in the bottom row of Fig. 7 demonstrated inhibition in both

312   TEOAE and SSOAE amplitudes in CAS+. The remaining 11 participants with SSOAEs and

313   inhibition also demonstrated this same trend. Results suggest that SSOAEs are not always

314   associated with enhancements.

315

316   *3.3 Growth of contralateral inhibition*

317   The growth in contralateral inhibition across elicitor intensities of 50 to 60 dB SPL was

318   compared for the three elicitors. For each participant, the slope for each elicitor was computed in

319   dB/dB as the difference in contralateral inhibition at 60 dB SPL minus contralateral inhibition at

320   50 dB SPL, divided by 10 dB. Box and whisker plots of growth across elicitor are shown in Fig.

321   8. Median growth of contralateral inhibition with increasing elicitor intensity was 0.11, 0.13, and

322   0.12 dB/dB for BBN, AM, and EM, respectively. At each elicitor type, three to four growth

323   values were negative, indicating that contralateral inhibition decreased as elicitor intensity

324   increased.

325   It was of interest to compare the growth in contralateral inhibition magnitude across the

326   two elicitor intensities; however, growth did not meet the assumptions of a one-way repeated

327   measures ANOVA. One outlier was present for AM growth, as evidenced by a studentized

328   residual that exceeded +3 standard deviations. Additionally, BBN growth was not normally

329   distributed as assessed by a Shapiro-Wilk test of normality on the studentized residuals ($p <$

330   0.05). Therefore, a Friedman nonparametric test was performed to compare median growth

331   across elicitors. The results revealed that there was no statistically significant difference in

332   growth across the three elicitor types, $\chi^2(2) = 3.630$, $p = 0.163$.

333

16

4. Discussion

4.1 Impact of static versus dynamic noises on contralateral inhibition

The purpose of the current study was to determine the impact of temporal characteristics of noise elicitors on the magnitude and growth of contralateral inhibition of TEOAEs. The noise elicitors all had the same long-term average spectrum and RMS amplitude to isolate the temporal effects of 100-Hz amplitude modulation and the envelope of a four-talker babble noise. Contrary to our hypothesis that BBN would elicit larger inhibition, there was no significant difference in the magnitude of contralateral inhibition across elicitors at 50 or 60 dB SPL. Additionally, there was no significant difference in the growth of inhibition across elicitors. The only statistically significant finding was that the magnitude of inhibition increased from 50 to 60 dB SPL, which was expected and has been demonstrated previously for BBN (Veuillet et al., 1991; Hood et al., 1996).

Our results are inconsistent with the findings of Maison and colleagues, who systematically investigated the impact of the frequency and depth of amplitude modulation of BBN (Maison et al., 1999; 2001) presented contralaterally during measurement of OAEs. Their work found that a modulation frequency of 100 Hz and modulation depth of 100% evoked the largest inhibition relative to other modulated and unmodulated stimuli. It is also of note that Maison et al. (1997) found similar results when using amplitude-modulated sinusoids as contralateral elicitors. The authors discussed that the results were consistent with physiologic data that includes the modulation transfer function of single MOC neuron fibers (Gummer et al., 1988) and encoding of amplitude modulation by chopper cells in the ventral cochlear nucleus (Frisina et al., 1990).

17

356   More recent work, including the current study, suggests that MOCR activation is similar

357   whether the stimuli are unmodulated or amplitude modulated. Boothalingam et al. (2014) found

358   no statistically significant difference in contralateral inhibition of stimulus frequency OAEs and

359   tone-burst OAEs for BBN that was either unmodulated or amplitude modulated at 100 Hz and

360   presented at 60 dB SPL. The authors observed a trend of decreased inhibition in response to AM

361   stimuli relative to unmodulated stimuli and speculated that the silent periods or "dips" in the AM

362   stimuli may reduce sustained activation of the MOCR given its onset time course of

363   approximately 275 ms (Backus and Guinan, 2006). Our results showed a similar trend (see Fig.

364   4). Our random selection of 8-s segments of the noise waveforms upon each presentation,

365   combined with a click rate of 19.53/s that would not synchronize with the AM or EM noise,

366   likely caused some TEOAEs to be recorded in the presence of modulations dips and some in the

367   presence of modulation peaks, which may have\ reduced the contralateral inhibition of TEOAEs

368   in response to AM and EM noise, relative to BBN. However, it is important to note that

369   Boothalingam et al. (2014) found no significant difference in contralateral inhibition when the

370   modulation frequency of the AM noise elicitor was synchronized versus unsynchronized to the

371   click presentation rate. The results of Kalaiah et al. (2017) also demonstrated no significant

372   difference in inhibition for unmodulated BBN and BBN that was amplitude-modulated at 4, 50,

373   and 100 Hz when presented at 60 dB SPL.

374   It is unclear why Maison and colleagues consistently found increased inhibition for 100-

375   Hz AM elicitors whereas more recent studies did not. All studies utilized low OAE-eliciting

376   stimulus levels (ranging from 55 to 65 dB peak SPL), so cochlear amplifier gain was presumably

377   adequate to allow for an MOCR-induced change in gain (Hood et al., 1996; Guinan, 2006).

378   Boothalingam et al. (2014) verified that the OAE-eliciting stimulus rate used by Maison's group

379 did not explain the increased inhibition for 100-Hz AM. All studies presented the contralateral

380 noises at 60 dB SPL, which likely ensured that the MEMR was not activated and allowed for

381 across-study comparisons. We added the 50 dB SPL condition to see if the difference in

382 inhibition across elicitor type was dependent upon elicitor intensity, but we found no significant

383 elicitor type × elicitor intensity interaction. Additionally, we found that contralateral inhibition

384 grew by 0.11 to 0.13 dB per 1-dB increase in elicitor intensity, which is broadly consistent with

385 previous work on BBN (Veuillet et al., 1991; Hood et al., 1996). It may be possible that subtle

386 differences related to the participants, OAE measurement, and/or OAE analysis may have

387 contributed to the discrepant findings regarding the impact of modulated noises on the MOCR.

388

389 *4.2 Implications for listening in noise*

390   Our results, combined with those of Boothalingam et al. (2014) and Kalaiah et al. (2017),

391 may suggest a real-world benefit of the MOCR for listening in background noise. MOCR

392 function is associated with reduced neural adaptation in response to BBN (Kawase et al., 1993)

393 and with the ability to understand speech in the presence of static BBN (Giraud et al., 1997;

394 Kumar and Vanaja, 2004; Mertes et al., 2017). If modulated noises encountered in typical

395 listening situations (e.g., multi-talker babble) also activate the MOCR, then benefits for speech-

396 in-noise understanding may be conferred. However, experimental examination of such benefits

397 would need to consider the confounding (although beneficial) effect of listening in the "dips" of

398 modulated noises, which have been shown to improve speech-in-noise abilities relative to

399 unmodulated noises (e.g., Festen and Plomp, 1990). Additionally, the contralateral inhibition

400 reported in the current study and related studies only represents the overall MOCR effect

401 computed across tens of seconds or more.

402   When examined in 2-ms portions, contralateral inhibition tended to be smaller from 8–10

403   ms relative to later time windows for all noise elicitors and noise intensities (Fig. 8). The

404   difference in contralateral inhibition across the elicitor types appeared to be minimal.

405   Velenovsky and Glattke (2002) found a considerable difference in contralateral inhibition across

406   elicitor types using a similar time analysis method, but the elicitors varied in their bandwidth,

407   whereas the bandwidth of elicitor types in the current study were identical. The finding of less

408   contralateral inhibition from 8–10 ms is consistent with a recent study which also showed a

409   plateau in contralateral inhibition after the 8–10 ms window (Kalaiah et al., 2017). It should be

410   noted that we did not analyze the time course of the MOCR in a systematic way, so we may have

411   missed important differences in how the MOCR is activated by the elicitors across shorter time

412   periods relevant to perceiving individual speech sounds during running speech (Backus and

413   Guinan, 2006). Measuring OAEs that are elicited with continuous stimuli, such as stimulus-

414   frequency and distortion-product OAEs, may be preferable to measuring TEOAEs for examining

415   such changes (e.g., Backus and Guinan, 2006; Harrison et al., 2008).

416   As noted in Sec. 4.1, the noise elicitors in the current study had the same long-term

417   spectrum. Kalaiah et al. (2017) included actual multi-talker babble stimuli (2, 4, and 6 talkers) as

418   contralateral elicitors, which substantially reduced the high-frequency energy relative to the

419   BBN. They found that the multi-talker babble only elicited mean inhibition values of ≤0.5 dB,

420   significantly lower than their mean inhibition of 1.5 dB for BBN. This may suggest that multi-

421   talker babble is a weak activator of the MOCR due to its low pass nature. However, multi-talker

422   babble may contain discernible speech that can draw the listener's attention and thus increase or

423   decrease MOCR activation (reviewed in Meric and Collet, 1994). Such an attentional effect

424   might be minimized by utilizing time-reversed multi-talker babble or through explicit

425   instructions to participants regarding how they should direct their attention during the

426   contralateral inhibition measurements.

427

428   *4.3 Inhibition versus enhancement of TEOAE amplitude*

429   Figure 6 demonstrates that a minority of participants exhibited enhancement, rather than

430   inhibition, of TEOAE amplitude with MOCR activation. Although these enhancements have

431   been found in other OAE-based studies of the MOCR (Hood et al., 1996; Goodman et al., 2013),

432   the enhancements are inconsistent with physiologic work demonstrating that the MOCR

433   decreases cochlear amplifier gain (Murugasu and Russell, 1996; Cooper and Guinan, 2006). One

434   potential cause of these enhancements is activation of the MEMR, which can decrease middle

435   ear impedance above 1 kHz and may serve to increase TEOAE amplitudes (Boothalingam and

436   Purcell, 2015). We found no evidence of MEMR activation as assessed by examining changes in

437   the stimulus amplitude measured in the ear canal, although we cannot rule out subtle impedance

438   changes not detected by our methodology. We also qualitatively investigated the contribution of

439   SSOAEs to these enhancements (Fig. 7). As described in Sec. 3.2, the MOCR may differentially

440   impact SSOAEs and TEOAEs and result in amplitude enhancements. All participants who

441   exhibited enhancements had SSOAEs in the 1000 to 2000 Hz region. However, some

442   participants who exhibited inhibition also had SSOAEs. It appears that SSOAEs may be

443   necessary, but not sufficient, for MOCR enhancements. Recent in work in guinea pigs has found

444   that MOCR enhancements in OAE amplitude may be caused by the MOCR increasing cochlear

445   roughness (and thus increased levels of reflection-source OAEs), at least when the MOCR is

446   elicited by electrical shocks (Berezina-Greene and Guinan, 2017). More work is needed to

447 understand the cause of MOCR enhancements in humans and their relevance to assessing MOCR

448 activity.

449

450 *4.4 Future directions*

451   More work is needed to better understand how the MOCR responds to a variety of noise

452 sources that vary in both spectral and temporal properties, and how the resulting efferent

453 response influences auditory perception. The methodology used in the current study was limited

454 to a contralateral presentation of the MOCR elicitors. Forward masking paradigms allow for

455 bilateral presentation of MOCR elicitors (Berlin et al., 1995) and would therefore provide insight

456 into the MOCR as it would behave in real-world binaural listening, although it does not allow for

457 an examination of simultaneous masking. We examined the change in TEOAE amplitude to

458 compare with previous studies but characterizing the change in both TEOAE amplitude and

459 phase may reveal subtle differences in how the MOCR responds to different temporal and

460 spectral characteristics of stimuli. Additionally, we only used one stimulus level to evoke

461 TEOAEs; it is possible that use of lower stimulus levels may provide more sensitive

462 measurement of contralateral inhibition that could reveal larger differences in MOCR activation

463 across elicitors. Using a more stringent SNR criterion (e.g., 20 dB; Goodman et al., 2013) would

464 reduce the impact of physiologic and instrumentation noise on measurements of contralateral

465 inhibition. However, this would reduce the number of participants included in the current study

466 and thus reduce statistical power. SNR could be increased by increasing the number of sweeps.

467 However, there may be a risk of introducing variability in attentional state between elicitor type

468 $\times$ elicitor intensity conditions by increasing the duration of measurements. Finally, experiments

469 that allow for concurrent measurements of the MOCR during perceptual tasks (e.g., Zhao et al.,

22

470   2014) will serve to bridge the gap between physiologic measurements of MOCR activity and the

471   functional relevance of the MOCR when listening to speech in background noise.

Acknowledgments

References

Abdala, C., Mishra, S., Garinis, A., 2013. Maturation of the human medial efferent reflex revisited. J. Acoust. Soc. Am. 133, 938–950. https://doi.org/10.1121/1.4773265

Abdala, C., Mishra, S.K., 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. https://doi.org/10.1121/1.3068442

Backus, B.C., Guinan Jr., J.J., 2006. Time-course of the human medial olivocochlear reflex. J. Acoust. Soc. Am. 119, 2889–2904. https://doi.org/10.1121/1.2169918

Backus, B.C., Guinan Jr., 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. https://doi.org/10.1007/s10162-007-0100-0

Berezina-Greene, M.A., Guinan Jr., J.J., 2017. Electrically evoked medial olivocochlear efferent effects on stimulus frequency otoacoustic emissions in guinea pigs. J. Assoc. Res. Otolaryngol. 18, 153–163. https://doi.org/10.1007/s10162-016-0593-5

Berlin, C.I., Hood, L.J., Hurley, A.E., Wen, H., Kemp, D.T., 1995. Binaural noise suppresses linear click-evoked otoacoustic emissions more than ipsilateral or contralateral noise. Hear. Res. 87, 96–103. https://doi.org/10.1016/0378-5955(95)00082-F

Berlin, C.I., Hood, L.J., Wen, H., Szabo, P., Cecola, R.P., Rigby, P., Jackson, D.F., 1993. Contralateral suppression of non-linear click-evoked otoacoustic emissions. Hear. Res. 71, 1-11. https://doi.org/10.1016/0378-5955(93)90015-s

Boothalingam, S., Purcell, D., Scollie, S., 2014. Influence of 100 Hz amplitude modulation on the human medial olivocochlear reflex. Neurosci. Lett. 580, 56–61. https://doi.org/10.1016/j.neulet.2014.07.048

25

507 Boothalingam, S., Purcell, D.W., 2015. Influence of the stimulus presentation rate on medial

508   olivocochlear system assays. J. Acoust. Soc. Am. 137, 724–732.

509   https://doi.org/10.1121/1.4906250

510 Brownell, W.E., 1990. Outer hair cell electromotility and otoacoustic emissions. Ear Hear. 11,

511   82–92. https://doi.org/10.1097/00003446-199004000-00003

512 Brungart, D.S., Simpson, B.D., Ericson, M.A., Scott, K.R., 2001. Informational and energetic

513   masking effects in the perception of multiple simultaneous talkers. J. Acoust. Soc. Am.

514   110, 2527–2538. https://doi.org/10.1121/1.1408946

515 Collet, L., Kemp, D.T., Veuillet, E., Duclaux, R., Moulin, A., Morgon, A., 1990. Effect of

516   contralateral auditory stimuli on active cochlear micro-mechanical properties in human

517   subjects. Hear. Res. 43, 251–261. https://doi.org/10.1016/0378-5955(90)90232-E

518 Cooper, N.P., Guinan Jr., J.J., 2006. Efferent-mediated control of basilar membrane motion. J

519   Physiol. 49–54. https://doi.org/10.1113/jphysiol.2006.114991

520 Festen, J.M., Plomp, R., 1990. Effects of fluctuating noise and interfering speech on the speech-

521   reception threshold for impaired and normal hearing. J. Acoust. Soc. Am. 88, 1725–1736.

522   https://doi.org/10.1121/1.400247

523 Frisina, R.D., Smith, R.L., Chamberlain, S.C., 1990. Encoding of amplitude modulation in the

524   gerbil cochlear nucleus: I. A hierarchy of enhancement. Hear. Res. 44, 99–122.

525   https://doi.org/10.1016/0378-5955(90)90074-Y

526 Giraud, A.L., Garnier, S., Micheyl, C., Lina, G., Chays, A., Chéry-Croze, S., 1997. Auditory

527   efferents involved in speech-in-noise intelligibility. Neuroreport 8, 1779–1783.

528   https://doi.org/10.1097/00001756-199705060-00042

529   Goodman, S.S., Fitzpatrick, D.F., Ellison, J.C., Jesteadt, W., Keefe, D.H., 2009. High-frequency

530   click-evoked otoacoustic emissions and behavioral thresholds in humans. J. Acoust. Soc.

531   Am. 125, 1014–1032. https://doi.org/10.1121/1.3056566

532   Goodman, S.S., Mertes, I.B., Lewis, J.D., Weissbeck, D.K., 2013. Medial olivocochlear-induced

533   transient-evoked otoacoustic emission amplitude shifts in individual subjects. J. Assoc.

534   Res. Otolaryngol. 14, 829–842. https://doi.org/10.1007/s10162-013-0409-9

535   Guinan Jr., J.J., 2006. Olivocochlear efferents: anatomy, physiology, function, and the

536   measurement of efferent effects in humans. Ear Hear. 27, 589–607.

537   https://doi.org/10.1097/01.aud.0000240507.83072.e7

538   Guinan Jr., J.J., Backus, B.C., Lilaonitkul, W., Aharonson, V., 2003. Medial olivocochlear

539   efferent reflex in humans: otoacoustic emission (OAE) measurement issues and the

540   advantages of stimulus frequency OAEs. J. Assoc. Res. Otolaryngol. 4, 521–540.

541   https://doi.org/10.1007/s10162-002-3037-3

542   Gummer, M., Yates, G.K., Johnstone, B.M., 1988. Modulation transfer function of efferent

543   neurones in the guinea pig cochlea. Hear. Res. 36, 41–52. https://doi.org/10.1016/0378-

544   5955(88)90136-0

545   Harrison, R.V., Sharma, A., Brown, T., Jiwani, S., James, A. L., 2008. Amplitude modulation of

546   DPOAEs by acoustic stimulation of the contralateral ear. Acta Otolaryngol. 128, 404–

547   407. https://doi.org/10.1080/00016480701784965

548   Hood, L.J., Berlin, C.I., Hurley, A., Cecola, R.P., Bell, B., 1996. Contralateral suppression of

549   transient-evoked otoacoustic emissions in humans: intensity effects. Hear. Res. 101, 113–

550   118. https://doi.org/10.1016/s0378-5955(96)00138-4

551   Kalaiah, M.K., Nanchirakal, J.F., Kharmawphlang, L., Noronah, S.C., 2017. Contralateral
552   suppression of transient evoked otoacoustic emissions for various noise signals. Hearing
553   Balance Commun., 15, 84–90. https://doi.org/10.1080/21695717.2017.1311504

554   Kawase, T., Delgutte, B., Liberman, M.C., 1993. Antimasking effects of the olivocochlear reflex.
555   II. Enhancement of auditory-nerve responses to masked tones. J. Neurophysiol. 70, 2533–
556   2549. https://doi.org/10.1152/jn.1993.70.6.2533

557   Kemp, D.T., 1978. Stimulated acoustic emissions from within the human auditory system. J.
558   Acoust. Soc. Am. 64, 1386–1391. https://doi.org/10.1121/1.382104

559   Kemp, D.T., Ryan, S., Bray, P., 1990. A guide to the effective use of otoacoustic emissions. Ear
560   Hear. 11, 93–105. https://doi.org/10.1097/00003446-199004000-00004

561   Khalfa, S., Veuillet, E., Collet, L., 1998. Influence of handedness on peripheral auditory
562   asymmetry. Eur. J. Neurosci. 10, 2731–2737. https://doi.org/10.1046/j.1460-
563   9568.1998.00286.x

564   Kumar, U.A., Vanaja, C.S., 2004. Functioning of olivocochlear bundle and speech perception in
565   noise. Ear Hear. 25, 142–146. https://doi.org/10.1097/01.AUD.0000120363.56591.E6

566   Lilaonitkul, W., Guinan Jr., J.J., 2009. Human medial olivocochlear reflex: effects as functions
567   of contralateral, ipsilateral, and bilateral elicitor bandwidths. J. Assoc. Res. Otolaryngol.
568   10, 459–470. https://doi.org/10.1007/s10162-009-0163-1

569   Lilly, D.J., Hutter, M.M., Lewis, M.S., Folmer, R., Shannon, J., 2011. Development of a "virtual
570   cocktail party" for the measurement of speech intelligibility in a sound field. J. Am.
571   Acad. Audiol. 22, 294–305. https://doi.org/10.3766/jaaa.22.5.6

572 Maison, S., Durrant, J., Gallineau, C., Micheyl, C., Collet, L., 2001. Delay and temporal
573   integration in medial olivocochlear bundle activation in humans. Ear Hear. 22, 65–74.
574   https://doi.org/10.1097/00003446-200102000-00007

575 Maison, S., Micheyl, C., Andéol, G., Gallégo, S., Collet, L., 2000. Activation of medial
576   olivocochlear efferent system in humans: influence of stimulus bandwidth. Hear. Res.
577   140, 111–125. https://doi.org/10.1016/s0378-5955(99)00196-3

578 Maison, S., Micheyl, C., Collet, C., 1997. Medial olivocochlear efferent system in humans
579   studied with amplitude-modulated tones. J. Neurophysiol. 77, 1759–1768.
580   https://doi.org/10.1152/jn.1997.77.4.1759

581 Maison, S., Micheyl, C., Collet, C., 1999. Sinusoidal amplitude modulation alters contralateral
582   noise suppression of evoked otoacoustic emissions in humans. Neuroscience 91, 133–
583   138.   https://doi.org/10.1016/S0306-4522(98)00608-3

584 Meric, C., Collet, L., 1994. Attention and otoacoustic emissions: a review. Neurosci. Biobehav.
585   Rev. 18, 215–222. https://doi.org/10.1016/0149-7634(94)90026-4

586 Mertes, I.B., Leek, M.R., 2016. Concurrent measures of contralateral suppression of transient-
587   evoked otoacoustic emissions and of auditory steady-state responses. J. Acoust. Soc. Am.
588   140, 2027–2038. https://doi.org/10.1121/1.4962666

589 Mertes, I.B., Wilbanks, E.C., Leek, M.R., 2017. Olivocochlear efferent activity is associated
590   with the slope of the psychometric function of speech recognition in noise. Ear Hear.
591   [Epub ahead of print]. https://doi.org/10.1097/AUD.0000000000000514

592 Murugasu, E., Russell, I.J., 1996. The effect of efferent stimulation on basilar membrane
593   displacement in the basal turn of the guinea pig cochlea. J. Neurosci. 16, 325–332.

594   Papsin, E., Harrison, A.L., Carraro, M., Harrison, R.V., 2014. Contralateral ear occlusion for

595   improving the reliability of otoacoustic emission screening tests. Int. J. Otolaryngol.

596   2014, 1–8. https://doi.org/10.1155/2014/248187

597   Prieve, B.A., Falter, S.R., 1995. COAEs and SSOAEs in adults with increased age. Ear Hear. 16,

598   521–528. http://doi.org/10.1097/00003446-199510000-00009

599   Prieve, B.A., Gorga, M.P., Schmidt, A., Neely, S., Peters, J., Schultes, L., Jesteadt, W., 1993.

600   Analysis of transient-evoked otoacoustic emissions in normal-hearing and hearing-

601   impaired ears. J. Acoust. Soc. Am. 93, 3308–3319. https://doi.org/10.1121/1.405715

602   Timpe-Syverson, G.K., Decker, T.N., 1999. Attention effects on distortion-product otoacoustic

603   emissions with contralateral speech stimuli. J. Am. Acad. Audiol. 10, 371–378.

604   Velenovsky, D.S., Glattke, T.J., 2002. The effect of noise bandwidth on the contralateral

605   suppression of transient evoked otoacoustic emissions. Hear. Res. 164, 39–48.

606   https://doi.org/10.1016/s0378-5955(01)00393-8

607   Veuillet, E., Collet, L., Duclaux, R., 1991. Effect of contralateral acoustic stimulation on active

608   cochlear micromechanical properties in human subjects: dependence on stimulus

609   variables. J. Neurophysiol. 65, 724–735. https://doi.org/10.1152/jn.1991.65.3.724

610   Winslow, R.L., Sachs, M.B., 1987. Effect of electrical stimulation of the crossed olivocochlear

611   bundle on auditory nerve response to tones in noise. J. Neurophysiol. 57, 1002–1021.

612   https://doi.org/10.1152/jn.1987.57.4.1002

613   Zhao, W., Strickland, E., Guinan, J., 2014. Measurement of medial olivocochlear efferent

614   activity during psychophysical overshoot. Assoc. Res. Otolaryngol. Abs. 37, 78–79.

615 **Figure captions**

616 **Fig. 1.** Waveforms of the three contralateral elicitors. Each panel displays the first 1000 ms.

617

618 **Fig. 2.** Example mean TEOAE waveforms obtained in CAS- and CAS+. Data are shown for a

619 representative participant in response to BBN at 60 dB SPL. Time is shown relative to the

620 stimulus peak location. TEOAE RMS amplitude decreased in CAS+ as expected.

621

622 **Fig. 3.** Mean TEOAE signal and noise floor amplitudes across elicitor type × elicitor intensity

623 conditions. The vertical dashed line separates results for intensities of 50 dB SPL (left) and 60

624 dB SPL (right). Error bars represent +1 SEM.

625

626 **Fig. 4.** Mean contralateral inhibition across elicitor type × elicitor intensity conditions. Error bars

627 represent +1 SEM.

628

629 **Fig. 5.** Analysis of contralateral inhibition in 2-ms time windows. The left and right panels

630 represent results obtained at elicitor intensities of 50 and 60 dB SPL, respectively. Bars represent

631 mean values. Error bars represent +1 SEM.

632

633 **Fig. 6.** Distribution of contralateral inhibition at each elicitor type × elicitor intensity condition.

634 Boxes encompass the middle 50% of the data. Thick horizontal lines within each box are the

635 medians. The whiskers extend to the largest and smallest values not considered outliers. Crosses

636 represent outliers. The gray horizontal line is used to separate inhibition (positive values) from

31

637   enhancement (negative values). The vertical dashed line separates results for elicitor intensities

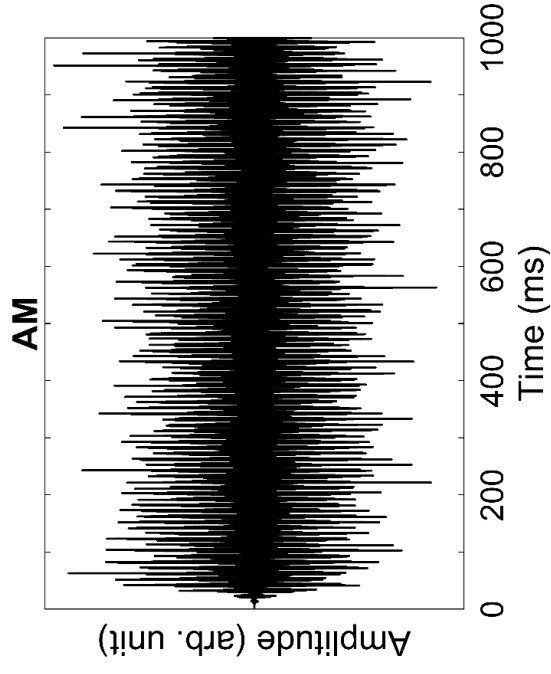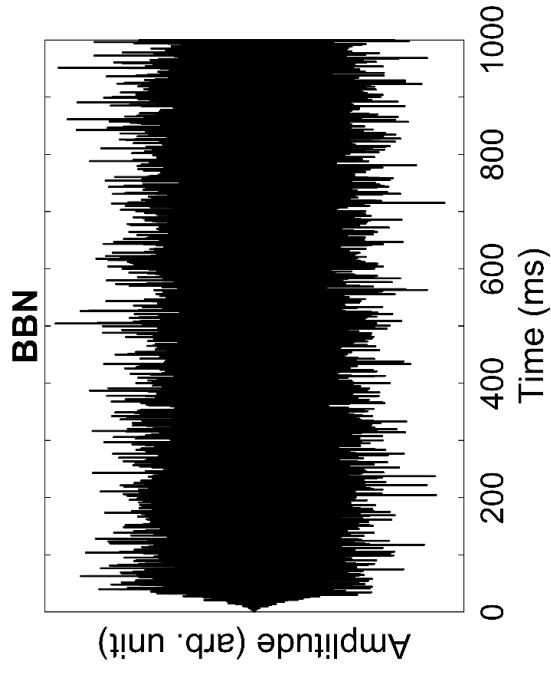638   of 50 dB SPL (left) and 60 dB SPL (right).

639

640   **Fig. 7.** Comparison of a participant with contralateral enhancement (top row) versus contralateral

641   inhibition (bottom row). Panels on the left show FFTs computed on the analysis window from 8

642   to 18 ms. Panels on the right show FFTs computed on the analysis window from 34 to 42 ms.

643   Thin dashed lines represent the recording noise floors in the CAS- (black) and CAS+ (gray)

644   conditions. Results were obtained for AM noise presented at 50 dB SPL.

645

646   **Fig. 8.** Distribution of growth in contralateral inhibition with increasing elicitor intensity. Boxes

647   encompass the middle 50% of the data. Thick horizontal lines within each box are the medians.

648   The whiskers extend to the largest and smallest values not considered outliers. Crosses represent

649   outliers. The gray horizontal line is used to visually separate positive from negative growth.
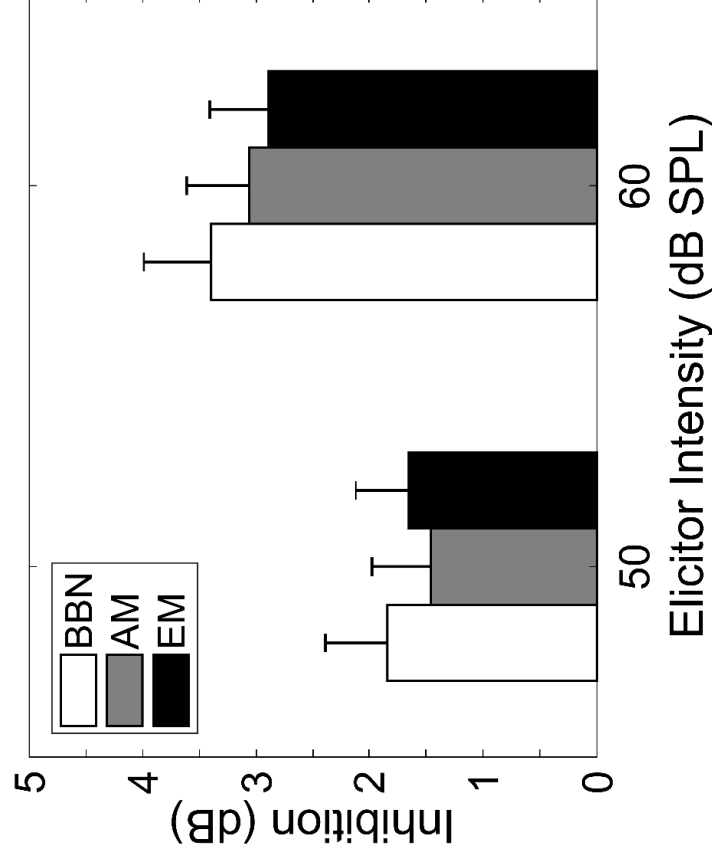
Footnotes
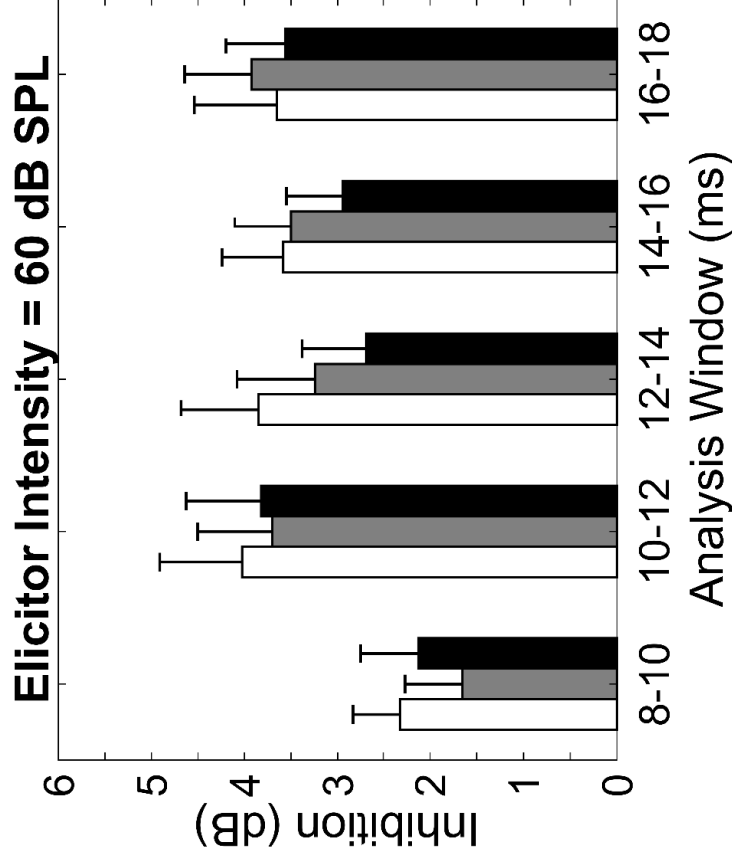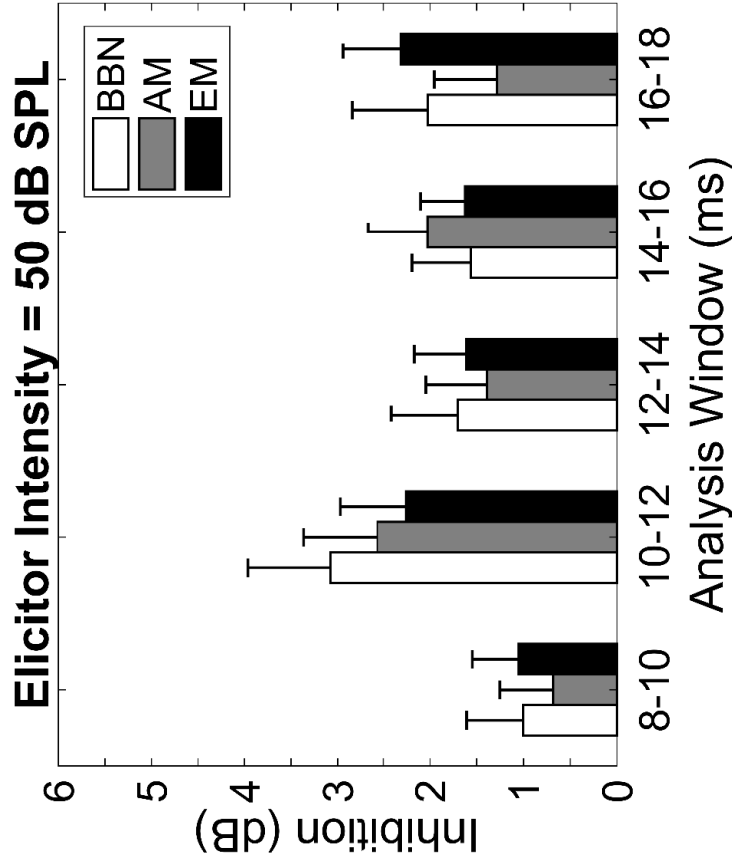
[1] Due to a programming error in the randomization sequence, the first two participants were inadvertently presented with the same order of contralateral noise conditions (elicitor $\times$ intensity). This error was subsequently corrected and did not affect the remaining participants.
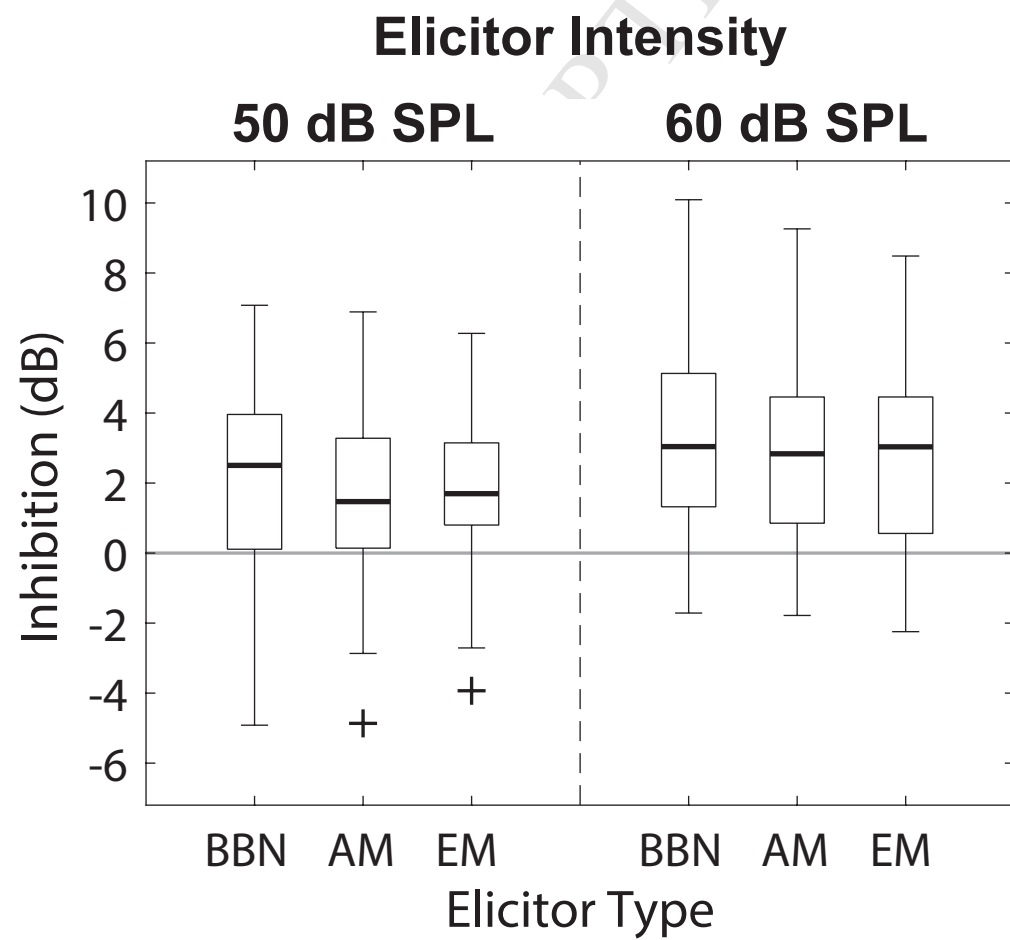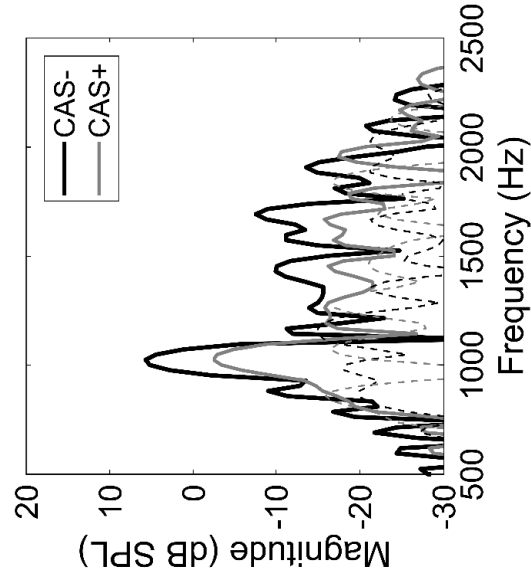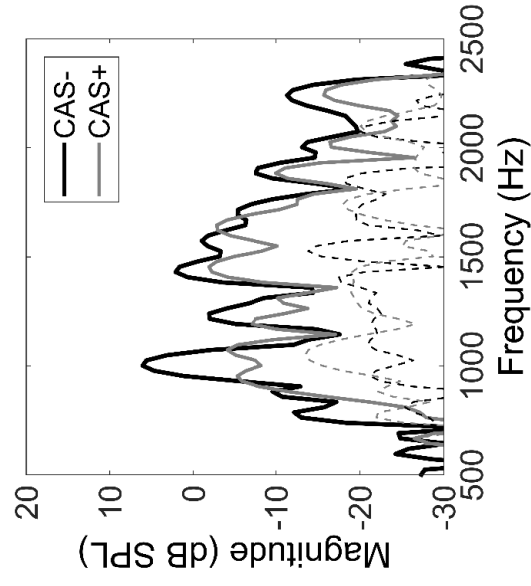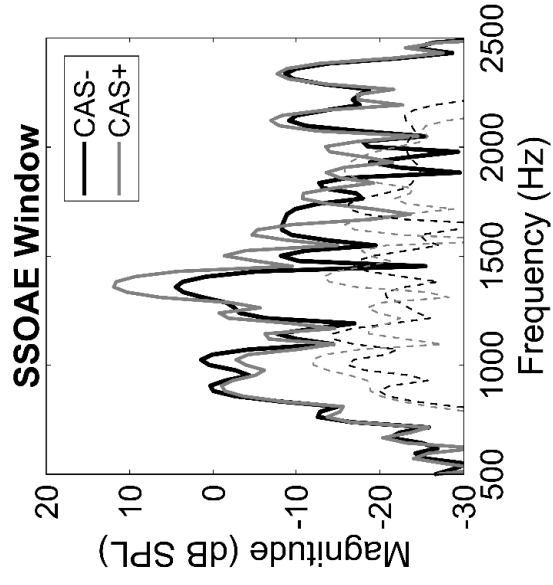
BBN

Amplitude (arb. unit)

Time (ms)

0   200   400   600   800   1000

AM

Amplitude (arb. unit)

Time (ms)

0   200   400   600   800   1000

EM

Amplitude (arb. unit)

Time (ms)

0   200   400   600   800   1000

Elicitor Intensity

50 dB SPL   **60 dB SPL**

TEOAE Window / **SSOAE Window**

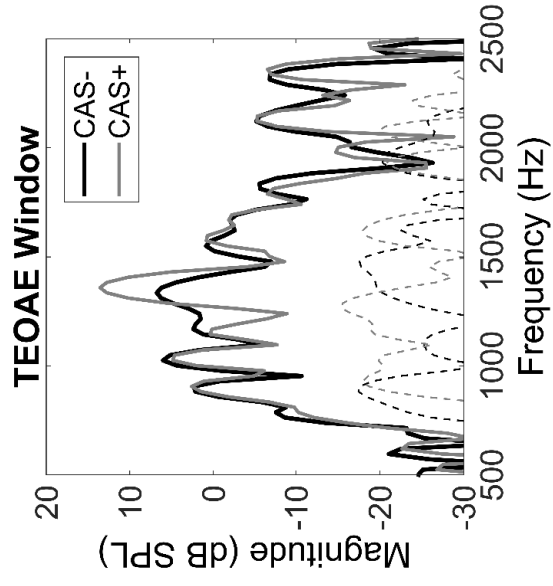Figure showing four panels of Magnitude (dB SPL) versus Frequency (Hz), with CAS− and CAS+ conditions.
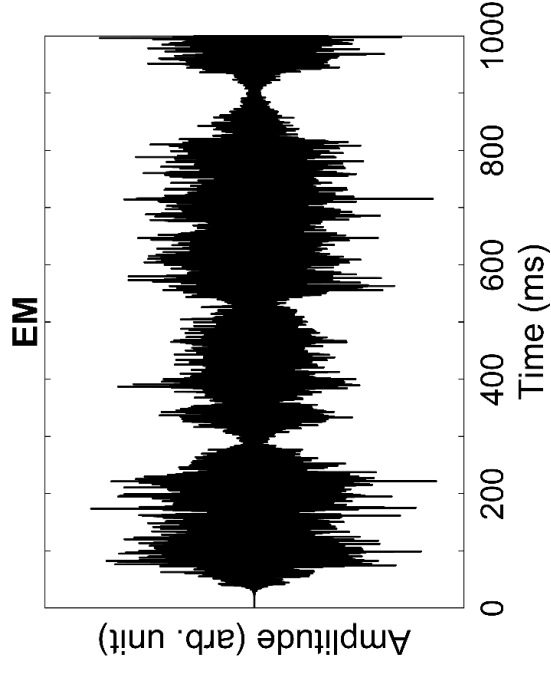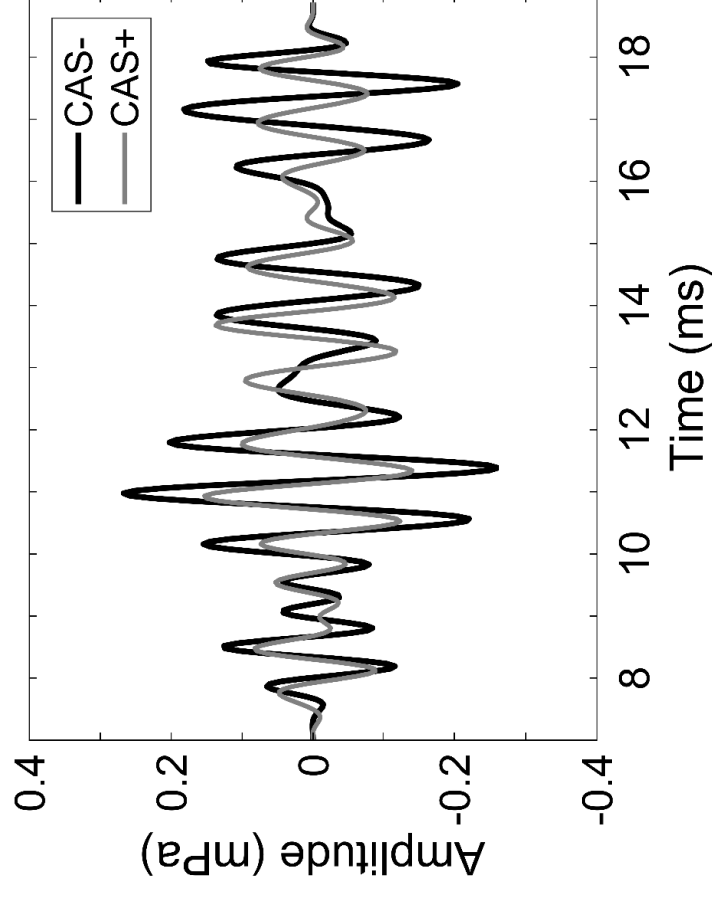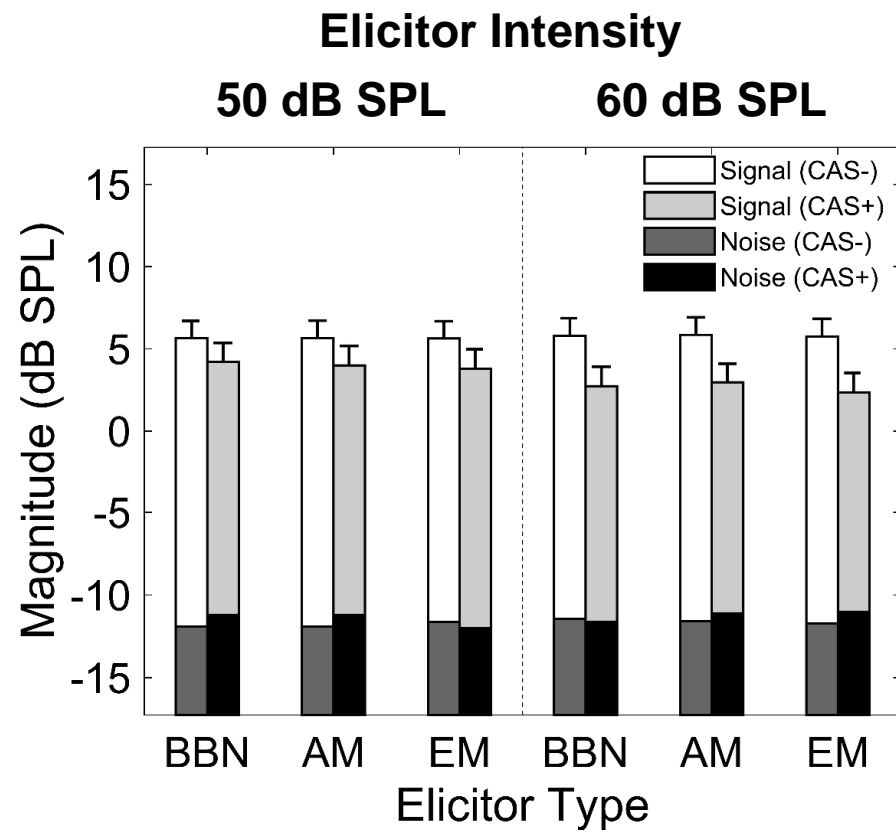
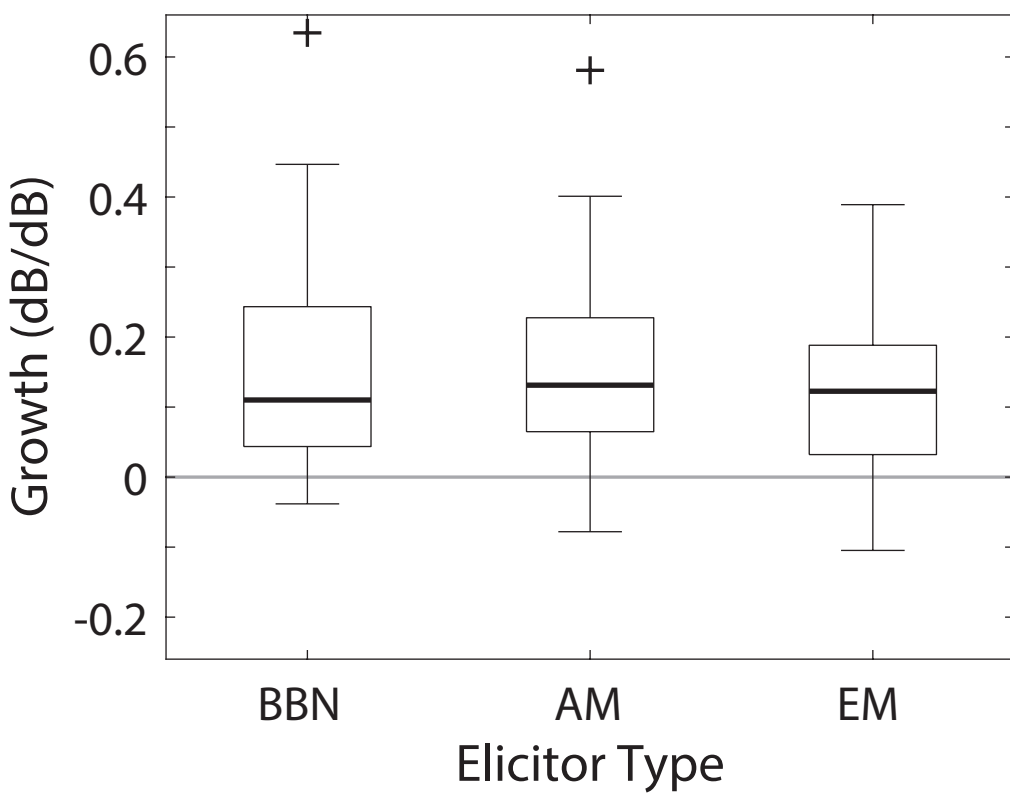1 **Highlights**

2 • MOCR responded similarly to dynamic and static noise elicitors

3 • MOCR enhanced rather than inhibited TEOAE amplitudes in minority of subjects

4 • Median MOCR growth was 0.11 – 0.13 dB per 1 dB increase in MOCR elicitor intensity