Hearing Research 367 (2018) 124–128

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Research Paper

Adversarial relationship between combined medial olivocochlear (MOC) and middle-ear-muscle (MEM) reflexes and alarm-in-noise detection thresholds under negative signal-to-noise ratios (SNRs)

Buddhika Karunarathne [a, b], Tingyi Wang [a, b], Richard H.Y. So [a, b, *], Anna C.S. Kam [c], Ray Meddis [d]

[a] HKUST-Shenzhen Research Institute, Shenzhen, 518057, China
[b] Department of Industrial Engineering and Decision Analytics, Clearwater Bay, Hong Kong University of Science and Technology, Hong Kong, China
[c] Department of Special Education and Counselling, Education University of Hong Kong, Hong Kong, China
[d] Department of Psychology, University of Essex, Colchester, CO4 3SQ, United Kingdom

A R T I C L E I N F O

Article history:
Received 16 September 2017
Received in revised form
28 June 2018
Accepted 25 July 2018
Available online 27 July 2018

Keywords:
Alarm-in-noise detection
MOCS efferent feedback
MEM reflex
Otoacoustic emissions
Loud noise

A B S T R A C T

The role of auditory efferent feedback from the medial olivocochlear system (MOCS) and the middle-ear-muscle (MEM) reflex in tonal detection tasks for humans in the presence of noise is not clearly understood. Past studies have yielded inconsistent results on the relationship between efferent feedback and tonal detection thresholds. This study attempts to address this inconsistency. Fifteen human subjects with normal hearing participated in an experiment where they were asked to identify an alarm signal in the presence of 80 dBA background (pink) noise. Masked detection thresholds were estimated using the method of two-interval forced choice (2IFC). Contralateral suppression of transient-evoked otoacoustic emissions (TEOAEs) was measured to estimate the strength of auditory efferent feedback. Subsequent correlation analysis revealed that the contralateral suppression of TEOAEs was significantly negatively correlated ($r = -0.526$, $n = 15$, $p = 0.0438$) with alarm-in-noise (AIN) detection thresholds under negative signal-to-noise conditions. The result implies that the stronger the auditory efferent feedback, the worse the detection thresholds and thus the poorer the tonal detection performance in the presence of loud noise.

1. Introduction

The olivocochlear bundle (OCB) comprises a lateral and a medial part with the medial olivocochlear (MOC) part connected to the outer hair cells (Warr and Guinan, 1979; Wagner et al., 2008). Scientists currently believe that the MOC bundle carries efferent feedback to outer hair cells to suppress the perception of loud sounds. Evidence on the relationship between MOC efferent feedback and cochlear function has been widely reported (Fex, 1967; Francis and Nadol, 1993; Mountain, 1980).

Animal studies have demonstrated that MOC efferent signals are associated with reductions in compound action potential and discharge rates in auditory nerve fibres (Galambos, 1956; Buno, 1978; Liberman, 1989; Wiederhold and Kiang, 1970). Based on evidence from these studies, Cody and Johnstone (1982) suggested that MOC efferents can suppress the perception of loud noise and mitigate its masking effects.

Nieder and Nieder (1970) and Dolan and Nuttal (1988) also suggested that the MOC can help to reduce noise masking effects. This anti-masking role of MOC efferents is, however, controversial. Dewson (1968) suggested that efferents played a part in discriminating complex sounds from noise, but later studies have indicated otherwise (Trahiotis and Elliott, 1970; Igarashi et al., 1979). Further investigations on the properties of efferent fibres reconfirmed the involvement of MOC efferents in the detection of signals in the presence of noise (Liberman, 1988; Langhans and Kohlrausch, 1992). The effect of MOC has been described as an increase in the effective signal-to-noise ratio (SNR) in the auditory nerve response resulting in the improvement of perception amid noise (Guinan, 2006, 2010; Kujawa and Liberman, 2001). Animal studies have suggested that MOC activity improves the auditory nerve response

* Corresponding author. HKUST-Shenzhen Research Institute, South Area, Hi-tech Park, Nanshan, Shenzhen 518057, China.
E-mail address: rhyso@ust.hk (R.H.Y. So).

https://doi.org/10.1016/j.heares.2018.07.013
0378-5955/

to background noise (Kawase et al., 1993; Winslow and Sachs, 1988) and thereby shifts the dynamic range of hearing (Dolan and Nutall, 1988; Kawase et al., 1993; Kujawa and Liberman, 2001). Studies using guinea pigs have suggested that auditory efferent feedback may help to inhibit the perception of continuous noise and increase the probability of detecting transient noise (Liberman and Guinan, 1998; Dolan and Nuttall, 1988).

Studies on automatic speech recognition (Brown et al., 2010; Clark et al., 2012) have shown that medial olivocochlear system (MOCS) efferent feedback improves recognition performance in a positive SNR setting (i.e., speech (signal) in the presence of quieter background pink noise). Psychoacoustic studies have also suggested a relationship between MOC efferents and tone-in-noise (TIN) detection in humans (Langhans and Kohlrausch, 1992). However, debate continues regarding whether the estimated strength of MOC efferents and signal-in-noise detection thresholds are positively correlated (Micheyl and Collet, 1996; Kumar and Vanaja, 2004), negatively correlated (Micheyl et al., 1995; Garinis et al., 2011), or even uncorrelated (Wagner et al., 2008).

A loud acoustic stimulus will trigger not only the MOC efferent effect but also middle-ear muscle (MEM) contraction. Zhao and Dhar (2010) reported that both MOC and MEM reflexes could be triggered at sound pressure levels (SPLs) above 70 dB. In this study, we assume that both MOC and MEM reflexes are active simultaneously at SPLs of 80 dB.

In summary, the physiology and behaviour of MOC efferents have been intensively studied in the past. Yet, their role in detecting tones or speech in the presence of noise remains to be fully established. In particular, mixed relationships have been reported between the strength of MOC efferents and signal-in-noise detection thresholds. In this study, we investigate the relationship between the estimated combined strength of MOC & MEM reflex and the alarm-in-noise (AIN) detection threshold under negative SNR conditions in the presence of 80 dBA noise.

2. Methodology

2.1. Alarm-in-noise threshold measurements

Control variables included alarm spectrum, noise spectrum, and the SPL of the 80 dBA noise. The alarm sound and noise used in this experiment were similar to those used in Karunarathne et al. (2014). In their study, inter-subject variability and minimum detection thresholds were examined. The temporal and spectral characteristics of the alarm signal and noise in this study are presented in Fig. 1 and Fig. 2, respectively. The alarm had its peak energy at 2 kHz and had a spectrum similar to that of the typical over-speed alarms found in trains. The noise had similar characteristics to those of the typical background noise inside a train cabin and its spectrum approximately resembled that of pink noise. The SPL of the noise was fixed at 80 dBA.

Detection thresholds were determined based on the traditional 79.4 percentile point on the psychometric functions by means of an adaptive two-interval forced choice (2IFC) method (Levitt, 1971) with a 3-down-1-up rule. The initial step size was 5 dB, and it was reduced to 1 dB after the first four reversals. Each run consisted of 50 trials. This methodology has been used in past studies (e.g. Saberi et al., 1991; Richards, 1992; Micheyl et al., 1995). A Matlab® (version R2012a) program was written to implement the method and the stimuli were presented monaurally (right ear) using Sennheiser HD600 headphones.

Each trial consisted of two consecutive audio segments separated by a 500 ms period of silence. Both segments contained noise but only one segment contained the alarm (target). The subject's task was to determine which of the two segments contained the alarm. The duration of the noise segment was 400 ms whereas the duration of the alarm was 100 ms. The alarm started 200 ms after the noise and ended 100 ms before the noise. All stimuli had 20 ms ramps at the beginning and at the end. The durations of the noise and the alarm were consistent with Micheyl et al. (1995).

Fifteen subjects (12 male, 3 female) with no history of hearing impairment participated in the experiment. The audiometry thresholds were measured according to recommended procedures (American National Standards Institute, 2004a). Air-conduction thresholds at 0.25, 0.5, 1, 2, 4, 6, and 8 kHz and bone-conduction thresholds at 0.5, 1, 2, and 4 kHz were obtained using a Madsen Itera II Audiometer with Telephonics TDH-50 headphones. All transducers were calibrated according to American national Standards institute S3.6-2004 specifications (ANSI, 2004b). All subjects had hearing thresholds equal to or better than 20 dB hearing loss and no significant air-bone gap. The hearing threshold differed between the two ears by 5 dB or less at all tested frequencies for all subjects. Tympanometry was conducted to assess the middle ear functions as reference data using the TympStar middle-ear analyzer from GSI Inc., USA. The subjects were aged between 20 and 31 years with an average of 26.9 (SD = 2.6).

2.2. Measurement of the suppression of otoacoustic emissions to estimate the strength of combined MOC and MEM reflexes

Otoacoustic emissions (OAEs) can be suppressed by contralateral noise stimulation through MOC efferent feedback: the stronger the MOC feedback, the larger the suppression. Therefore, the contralateral suppression of transient-evoked OAEs (TEOAEs) has been used as a measure of the strength of MOC efferent feedback (e.g. Micheyl and Collet, 1996; Collet et al., 1990; Veuillet et al., 1991; Micheyl et al., 1995; Garinis et al., 2011). This study adopted a similar methodology to assess the combined MOC and MEM reflex strength of all 15 subjects who participated in AIN threshold measurements.

TEOAE measurement was conducted in a sound-proof booth at the Audiology Clinic of the Prince of Wales Hospital in Hong Kong. The Otodynamics® Echoport ILO292-II system was used to measure the TEOAEs of the subjects. The system used the ILO V6 software provided by Otodynamics Ltd.

Linear clicks were used as the evoking stimuli at an SPL of 60 dB. A linear stimulus was selected according to the manufacturer's recommendation for contralateral stimulation (Otodynamics Ltd, 2011). Broadband noise at 80 dB SPL was presented to the contralateral ear. The stimuli were presented at a rate of approximately 49 times per second (one stimulus every 20.48 ms). Each click stimulus lasted for 80 μs. The analysis window was 2.5–20 ms, automatically set by the equipment. The responses were bandpass-filtered between 0.5kHz and 6 kHz. Averaging was stopped when 260 responses below the rejection threshold were obtained.

Contralateral TEOAE suppression was determined using two separate OAE recordings. One recording was made when the masking noise was presented to the contralateral ear. The other recording was made in the absence of the masking noise. These two recordings were alternated at regular intervals to minimize the effects of bias due to the ordering of the tests. The difference in TEOAE response was calculated based on separate sums of the TEOAE response magnitudes with and without the contralateral noise.

The participants were asked to sit still with the OAE probes inserted into their ear canals. The probe to the left ear played the contralateral noise and the probe to the right ear measured the OAEs. The right ear was selected consistent with past studies (e.g., Bhagat and Carter, 2010; Micheyl et al., 1995, Micheyl and Collet, 1996). The participants were instructed to remain silent during the measurement procedure.

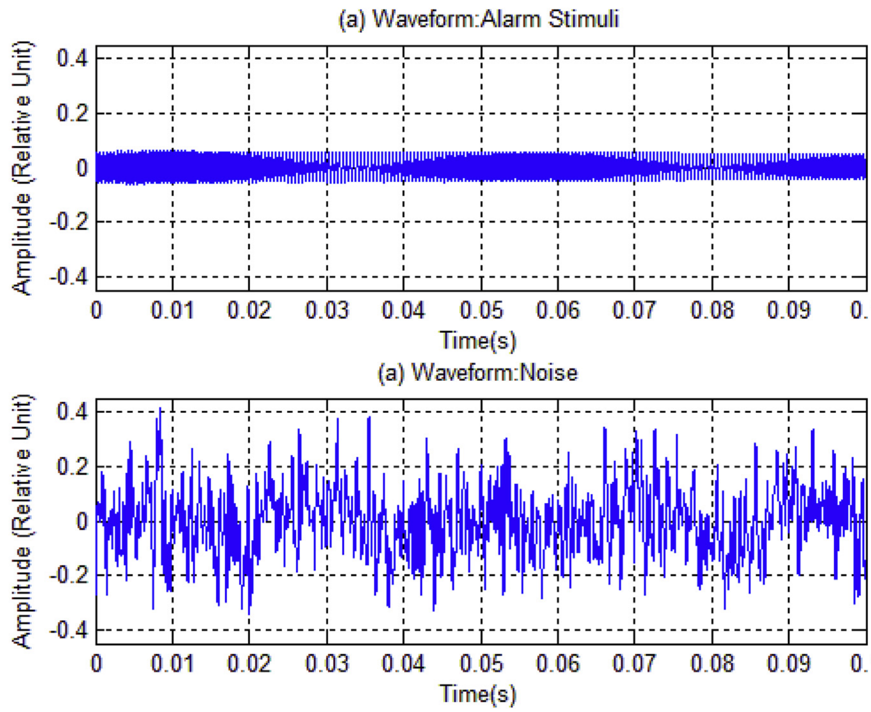

Fig. 1. Temporal characteristics of (a) the alarm and (b) the Noise.

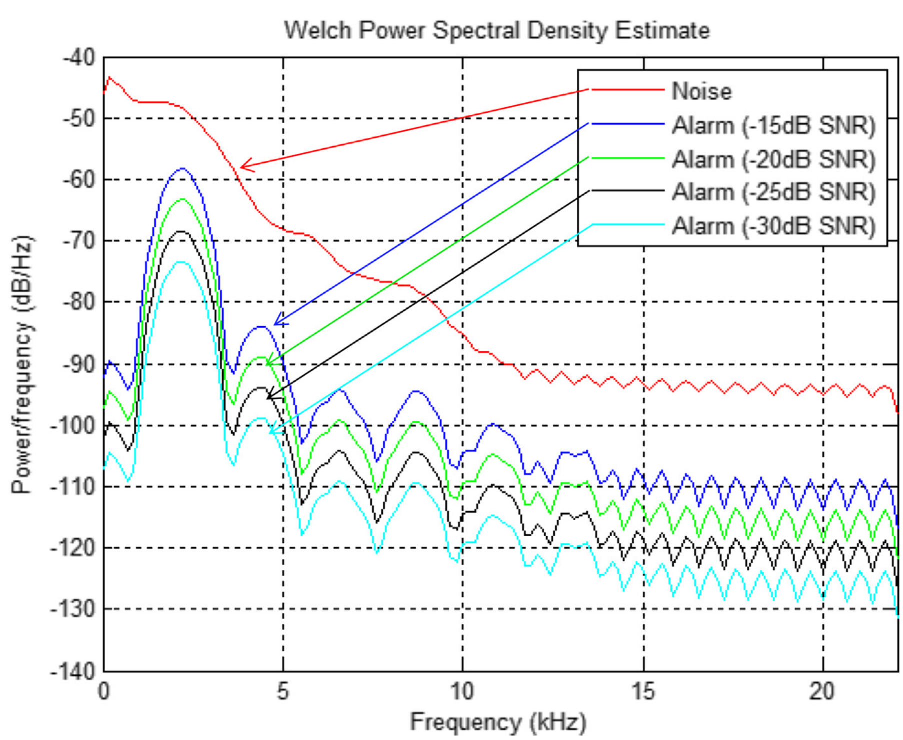

Fig. 2. Spectral Characteristics of the Alarm and the Noise (at SNRs of −15, −20, −25 and −30 dB).

3. Results and data analyses

The mean AIN detection threshold or SNR was −14.4 dB (SD = 3.1). Contralateral suppression of TEOAEs was derived by calculating the difference between the OAEs recorded when the masking noise was absent and present.

Data obtained on TEOAE contralateral suppression and monaural detection of AIN were analysed for Pearson correlations. A statistically significant negative correlation was obtained between individual levels of TEOAE contralateral suppression and individual monaural detection thresholds of AIN ($r = -0.526$, $n = 15$, $p = 0.0438$). The corresponding scatter plot is shown in

Fig. 3. As a control measure, tympanometry data were recorded. No significant correlation was obtained between individuals' tympanometry data and TEOAE contralateral suppression levels ($p > 0.3$, Pearson).

4. Discussion

The physiology and behaviour of how the MOCS and MEM mitigate the masking effect of noise under positive SNRs have been the subject of many studies (e.g., Micheyl and Collet, 1996; Kumar and Vanaja, 2004). This study instead explored the possibility that combined MOC and MEM reflexes might enhance the ability to detect a quiet alarm in the presence of a loud 80 dBA noise. We hypothesized that the stronger the combined MOC and MEM reflexes, the lower the AIN detection threshold. To our surprise, the opposite was found. A review of the literature reveals contradictory results. A summary of the available literature on this topic is given in Table 1.

As summarized in Table 1, Micheyl and Collet (1996) and Bhagat and Carter (2010) reported a significant positive correlation between tone-in-noise (TIN) detection thresholds and the strength of MOC efferent feedback. Micheyl et al. (1995) and Garinis et al. (2011) found a significant negative correlation. Wagner et al. (2008) could not find any significant correlation between speech-in-noise (SIN) detection and the strength of MOC efferent feedback. The current study observed a significant negative correlation between AIN detection thresholds and MOC efferent feedback and thus supports the findings of Micheyl et al. (1995) and Garinis et al. (2011).

This study differs from related past studies in that a loud (80 dBA) noise was used. The highest noise level used in past studies was 70 dB by Micheyl et al. (1995). Therefore the current study contributes to substantiating the findings of Micheyl et al. (1995) and Garinis et al. (2011) for higher noise levels.

A negative correlation between AIN detection thresholds and the strength of MOC efferent feedback indicates that stronger combined MOC and MEM reflexes were associated with a weaker AIN detection performance. Inspection of Table 1 reveals that the diverse findings in the literature can be reconciled by the following hypothesis: (i) under positive SNR listening conditions, MOC feedback improves SIN performance; (ii) under negative SNR listening conditions, MOC feedback does not affect SIN performance significantly; and (iii) MOC feedback degrades TIN performance under negative SNR listening conditions. This hypothesis suggests a pattern of positive efferent effects at positive SNRs and negative efferent effects at negative SNRs. If the hypothesis is correct, the seemingly mixed results shown in Table 1 would make sense. There are two exceptions, however. Bhagat and Carter (2010) found a significant positive correlation between MOC efferent feedback and masked detection thresholds only at 1 kHz but no correlation whatsoever at 2 kHz under negative SNR conditions. Therefore, their results do not make a strong case for the suggestion that MOC efferent feedback is positively correlated with masked detection thresholds under a negative SNR. Micheyl and Collet (1996) also observed a positive correlation between MOC feedback and masked detection thresholds even though the SNR was negative. However, the reported correlation between TEOAE suppression and a shift in the contralaterally-induced threshold was only observed in a subset of subjects (who first performed the detection task under contralateral stimulation).

It is not immediately obvious why efferent suppression should improve detection thresholds under positive SNR conditions but degrade them under negative SNR conditions. The cochlea is nonlinear and MEM and MOC effects can be complex. MOC effects, in particular, depend on the level and frequency content of the masker and the maskee in complex ways. Future research to continue to explore the effects of positive and negative SNRs is desirable.

5. Conclusion

The strength of MOC and MEM reflexes in individuals was estimated in this study by measuring the contralateral suppression of evoked OAEs. To our initial surprise, instead of improving the detection performance, combined MOC and MEM reflexes degraded the ability to detect a weak alarm (i.e. one with a low

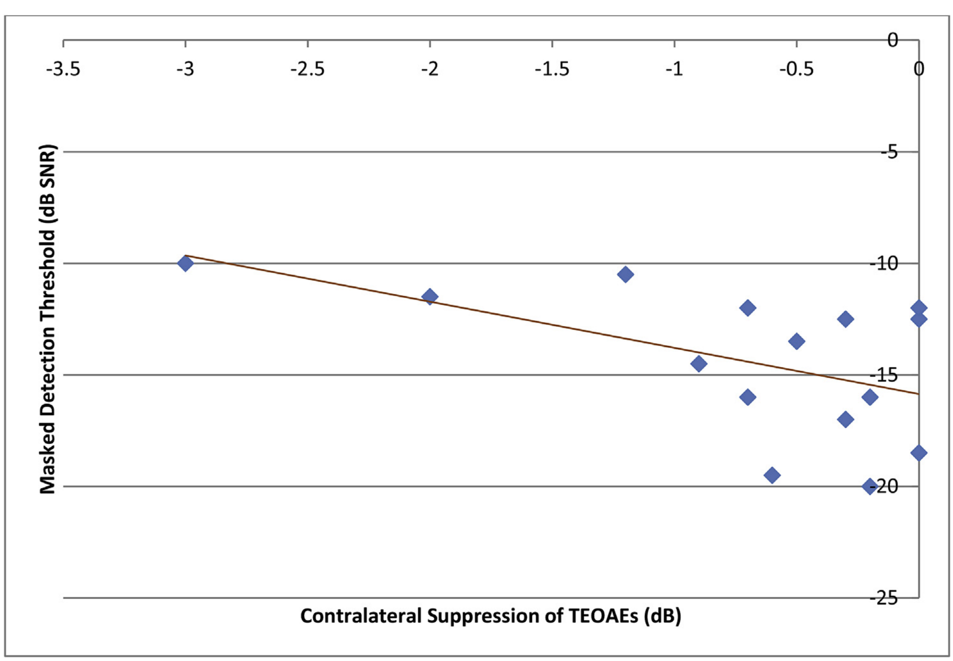

Fig. 3. Relationship between the contralateral suppression of TEOAEs and AIN detection thresholds (monaural).

Table 1
Comparison of past studies and the current study on the relationship between MOC efferents and tonal/speech detection in the presence of noise.

Study	Type of Target Stimuli	SNR	MOC-Threshold Relationship
Studies supporting the hypothesis that a negative SNR leads to a negative correlation			
Current study	Tonal	Negative	Negative
Garinis et al. (2011)	Tonal	Negative	Negative
Micheyl et al. (1995)	Tonal	Negative	Negative
Studies supporting hypothesis that a positive SNR leads to a positive correlation			
Kumar and Vanaja (2004)	Speech	Positive	Positive
Studies contradicting the findings reported in this study			
Bhagat and Carter (2010)	Tonal	Negative	Positive (at 1 kHz but not at 2 kHz))
Micheyl and Collet (1996)	Tonal	Negative	Positive (1 of 2 groups)

sound level) in the presence of a loud 80 dBA noise (i.e. negative SNR conditions). This suggests that individuals with stronger MOC and MEM reflexes have higher AIN detection thresholds when the alarm level is *below* the noise level. The seemingly contradictory findings in the literature on the benefits of MOC efferent feedback for signal-in-noise detection can be reconciled if the effects of MOC and MEM suppression depend on whether the SNR is positive or negative. Further work is thus desirable.

Acknowledgements

The authors would like to thank the Science Technology and Innovation Commission of Shenzhen Municipality (深圳市科技创新委员会) for partially supporting the work (grant no. JCYJ20170413173515472).

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heares.2018.07.013.

References

American National Standards Institute, 2004a. Methods for Manual Pure-tone Threshold Audiometry (ANSI S3.21). New York.
American National Standards Institute, 2004b. Specifications for Audiometers (ANSI S3.6-2004). New York.
Bhagat, S.P., Carter, P.H., 2010. Efferent-induced change in human cochlear compression and its influence on masking of tones. Neurosci. Lett. 485 (2010), 94–97.
Brown, G.J., Ferry, R.T., Meddis, R., 2010. A computer model of auditory efferent suppression: implications for the recognition of speech in noise. J. Acoust. Soc. Am. 127 (2), 943–954.
Buno Jr., W., 1978. Auditory nerve fiber activity influenced by contralateral ear sound stimulation. Exp. Neurol. 59, 62–74.
Clark, N.R., Brown, G.J., Jurgens, T., Meddis, R., 2012. A frequency-selective feedback model of auditory efferent suppression and its implications for the recognition of speech in noise. J. Acoust. Soc. Am. 132 (3), 1535–1541.
Cody, A.R., Johnstone, B.M., 1982. Temporary threshold shift modified by binaural acoustic stimulation. Hear. Res. 6, 199–205.
Collet, L., Kemp, D.T., Veuillet, E., Duclaux, R., Moulin, A., Morgon, A., 1990. Effects of contralateral auditory stimuli on active cochlear micromechanical properties in human subjects. Hear. Res. 43, 251–262.
Dewson, J.H., 1968. Efferent olivo-cochlear bundle: some relationships to stimulus discrimination in noise. J. Neurophysiol. 31, 122–130.
Dolan, D., Nuttall, A., 1988. Masked cochlear whole-nerve response intensity functions altered by electrical-stimulation of the crossed olivocochlear bundle. J. Acoust. Soc. Am. 83, 1081–1086.
Fex, J., 1967. Efferent inhibition in the cochlea related to hair-cell dc activity: study of postsynaptic activity of the crossed olivocochlear fibers in the cat. J. Acoust. Soc. Am. 1 (3), 666–675.
Francis, H.W., Nadol Jr., J.B., 1993. Patterns of innervation of outer hair cells in a chimpanzee: I. Afferent endings and reciprocal synapses. Hear. Res. 64, 184–190.
Galambos, R., 1956. Suppression of auditory nerve activity by stimulation of efferent fibers to cochlea. J. Neurophysiol. 19, 424–437.
Garinis, A., Werner, L., Abdala, C., 2011. The relationship between MOC reflex and masked threshold. Hear. Res. 282 (1–2), 128–137.
Guinan Jr., J.J., 2006. Olivocochlear efferents: anatomy, physiology, function, and the measurement of efferent effects in humans. Ear Hear. 27, 589–607.
Guinan Jr., J.J., 2010. Cochlear efferent innervation and function. Curr. Opin. Otolaryngol. Head Neck Surg. 18 (5), 447–453.
Igarashi, M., Cranford, J.L., Nakai, Y., Alford, B.R., 1979. Behavioral auditory function after transection of crossed olivo-cochlear bundle in the cat. IV. Study on pure-tone frequency discrimination. Acta Otolaryngol. 87 (1–2), 79–83.
Karunarathne, B., So, R.H.Y., Kam, A.C.S., 2014. Alarm vigilance in the presence of 80dBA pink noise with negative signal-to-noise ratios. In: Sharples, Sarah, Shorrock, Steven (Eds.), Contemporary Ergonomics 2014. Taylor & Francis, pp. 443–449.
Kawase, T., Delgutte, B., Liberman, M.C., 1993. Antimasking effects of the olivocochlear reflex. II. Enhancement of auditory-nerve response to masked tones. J. Neurophysiol. 70 (6), 2533–2549.
Kujawa, S., Liberman, C.M., 2001. Effects of olivocochlear feedback on distortion product otoacoustic emissions in Guinea pig. J. Assoc. Res. Otolaryngol 2, 268–278.
Kumar, U.A., Vanaja, C.S., 2004. Functioning of olivocochlear bundle and speech perception in noise. Ear Hear. 2004 (25), 142–146.
Langhans, A., Kohlrausch, A., 1992. Differences in auditory performance between monaural and diotic conditions. I: masked thresholds in frozen noise. J. Acoust. Soc. Am. 91 (6), 3456–3470.
Levitt, H., 1971. Transformed up-down methods in psychoacoustics. J. Acoust. Soc. Am. 49 (2), 467–477.
Liberman, M.C., 1988. Response properties of cochlear efferent neurons: monaural vs binaural simulation and the effect of noise. J. Neurophysiol. 60 (5), 1779–1789.
Liberman, M.C., 1989. Rapid assessment of sound-evoked olivocochlear feedback: suppression of compound action potential by contralateral sound. Hear. Res. 38, 47–56.
Liberman, M.C., Guinan, J.J., 1998. Feedback control of the auditory periphery: anti-masking effects of middle ear muscles vs. olivocochlear efferents. J. Commun. Disord. 31, 471–482.
Micheyl, C., Morlet, T., Giraud, A.L., Collet, L., Morgon, A., 1995. Contralateral suppression of evoked otoacoustic emissions and detection of a multi-tone complex in noise. Acta Otolaryngol. 115 (2), 178–182.
Micheyl, C., Collet, L., 1996. Involvement of the olivocochlear bundle in the detection of tones in noise. J. Acoust. Soc. Am. 99 (3), 1604–1610.
Mountain, D.C., 1980. Changes in endolymphatic potential and crossed olivocochlear bundle stimulation after cochlear mechanics. Science 210 (4465), 71–72.
Nieder, P., Nieder, I., 1970. Antimasking effect of crossed olivocochlear bundle stimulation with loud clicks in Guinea pig. Exp. Neurol. 28, 179–188.
Otodynamics Ltd, 2011. ILOV6: Clinical OAE Analysis and Data Analysis. The United Kingdom.
Richards, V.M., 1992. The detectability of a tone added to narrow bands of equal-energy noise. J. Acoust. Soc. Am. 91, 3424–2435.
Saberi, K., Dostal, L., Sadralodabai, T., Bull, V., Perrott, D.R., 1991. Free-field release from masking. J. Acoust. Soc. Am. 90, 1355–1370.
Trahiotis, C., Elliott, D.N., 1970. Behavioral investigation of some possible effects of sectioning the crossed olivocochlear bundle. J. Acoust. Soc. Am. 47, 592–596.
Veuillet, E., Collet, L., Duclaux, R., 1991. Effect of contralateral auditory stimulation on active cochlear micro-mechanical properties in human subjects: dependence on stimulus variables. J. Neurophysiol. 65 (3), 724–735.
Wagner, W., Frey, K., Heppelmann, G., Plontke, S.K., Zenner, H., 2008. Speech-in-noise intelligibility does not correlate with efferent olivocochlear reflex in humans with normal hearing. Acta Otolaryngol. 2008 (128), 53–60.
Warr, W.B., Guinan Jr., J.J., 1979. Efferent innervation of the organ of Corti: two separate systems. Brain Res. 173, 152–155.
Wiederhold, M.L., Kiang, N.Y.S., 1970. Effects of electrical stimulation of the crossed olivocochlear bundle on single auditory nerve fibers in cat. J. Acoust. Soc. Am. 48, 950–965.
Winslow, R.L., Sachs, M.B., 1988. Single-tone intensity discrimination based on auditory-nerve rate responses in backgrounds of quiet, noise, and with stimulation of crossed olivocochlear bundle. Hear. Res. 35, 165–190.
Zhao, W., Dhar, S., 2010. The effect of contralateral acoustic stimulation on spontaneous otoacoustic emissions. Journal of the Association for Research in Otolaryngology 11 (1), 53–67.