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Role of Active Listening and Listening Effort on Contralateral Suppression of Transient Evoked Otoacousic Emissions

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Background and Objectives: The present study aimed to investigate the effect of active listening and listening effort on the contralateral suppression of transient evoked otoacoustic emissions (CSTEOAEs). **Subjects and Methods**: Twenty eight young adults participated in the study. Transient evoked otoacoustic emissions (TEOAEs) were recorded using 'linear' clicks at 60 dB peSPL, in three contralateral noise conditions. In condition 1, TEOAEs were obtained in the presence of white noise in the contralateral ear. While, in condition 2, speech was embedded into white noise at +3, -3, and -9 dB signal-to-noise ratio (SNR) and delivered to the contralateral ear. The SNR was varied to investigate the effect of listening effort on the CSTEOAE. In condition 3, speech was played backwards and embedded into white noise at -3 dB SNR. The conditions 1 and 3 served as passive listening condition and the condition 2 served as active listening condition. In active listening condition, the participants categorized the words in to two groups (e.g., animal and vehicle). **Results**: CSTEOAE was found to be largest in the presence of white noise, and the amount of CSTEOAE was not significantly different between active and passive listening conditions (condition 2 and 3). Listening effort had an effect on the CSTEOAE, the amount of suppression increased with listening effort, when SNR was decreased from +3 dB to -3 dB. However, when the SNR was further reduced to -9 dB, there was no further increase in the amount of CSTEOAE, instead there was a reduction in the amount of suppression. **Conclusions**: The findings of the present study show that listening effort might affect CSTEOAE. **J Audiol Otol 2017;21(1):1-8**

KEY WORDS: OAE · Active listening · TEOAE suppression · Listening effort.

Introduction

The mammalian auditory system comprises of afferent and efferent pathways [1-3], and they interact with each other while processing the auditory information [4-6]. The efferent system consists of a network of descending pathways, arising from auditory cortex and terminating at outer hair cells and auditory nerve in the cochlea. Corticofugal projections from auditory cortex to superior olivary complex is referred as the corticofugal pathways [7], and the terminal branch from superior olivary complex to the cochlea is known as olivocochlear bundle [1]. Olivocochlear bundle is composed of lateral and medial components called as lateral and medial olivocochlear bundle respectively. Lateral olivocochlear bundle projects from superior olivary complex to dendrites of auditory nerve supplying the inner hair cells, and medial olivocochlear bundle projects from superior olivary complex to the outer hair cells in the cochlea [1-3]. Several investigations have been carried out to understand the function of efferent system during auditory processing, but these investigations have mainly focused on the role of olivocochlear bundle [6,8,9]. Further, corticofugal pathways have received little attention, and its role during auditory processing is not well understood [5,10,11].

The role of efferent auditory system on speech perception in noise has been investigated by correlating speech intelligibility in noise and contralateral suppression of otoacoustic emissions (OAE) [6,8,9,12,13]. Majority of these investigations have found a significant correlation between speech intelligibility in noise and suppression of OAEs [6,8,12,13]. In contrast, no relation between speech intelligibility and suppression of OAEs has also been reported [9]. This discrepancy in the findings has been attributed to the task differences used to measure speech perception. In the above mentioned studies, suppression of OAEs was measured in passive listening condition while speech perception was measured in active listening condition. Here, due to differences in the listening conditions, between speech perception and contralateral suppression tasks, it could be possible that the contribution of efferent system would differ. In speech perception task, which is an active listening condition, there could be involvement of both olivocochlear bundle and corticofugal pathways [5,14]. In contrast, olivocochlear bundle alone would be involved while measuring contralateral suppression of OAE, due to passive listening condition [5,14].

Measuring both speech perception and contralateral suppression of OAE in active listening conditions could help in better understanding the role of efferent auditory system during speech perception. Several investigations have assessed the effects of attention or active listening on the suppression of OAEs, but most of these investigations have used non-speech stimulus to draw attention of the participants [10,11]. Hence, there is dearth of studies which measure suppression of OAE in active listening condition, with direct focus on speech [5,14]. Garinis, et al. [5] investigated the effect of active listening condition on the contralateral suppression of transient evoked otoacoustic emission (TEOAE) using speech stimuli. They found a significantly greater contralateral suppression of TEOAE during active listening condition, which was attributed to cortical influence on the efferent suppression. Similarly, Smith and Cone [14] investigated the effect of active listening on contralateral suppression of TEOAE by varying task difficulty among children. They reported a systematic increase in the amount of suppression of OAE with increased task difficulty, suggesting that listening condition affects suppression of OAEs. Although findings of both investigations shows that active listening has an influence on the efferent activity, further research is required to generalize these findings. Hence, the present study was carried out to investigate the effect of listening conditions on the contralateral suppression of TEOAE.

Understanding speech in adverse listening conditions (e.g., noise) is an effortful process. To maintain optimal understanding, in noisy listening conditions, listeners must remove ambiguity and recover speech that has been degraded by noise. This process requires listeners to use their cognitive resources to understand speech in adverse listening conditions, referred to as ‘listening effort’ [15,16]. In addition to adverse listening conditions, hearing loss also causes increased listening effort as shown in several investigations [16]. Previous studies have shown that signal-to-noise ratio (SNR) has an effect on the listening effort, generally, higher listening effort is required for better understanding of speech in poorer SNRs [17,18]. It could be possible that the listening effort may have an influence on the efferent auditory activity, which in turn can influence the contralateral suppression of TEOAEs. Further, the amount of listening effort could also influence the strength of efferent activity. Thus, the present study is also aimed at investigating the effect of listening effort, by varying the SNRs of contralateral noise, on the contralateral suppression of TEOAEs. The hypotheses of this study were that 1) cortical processes engaged during active listening increase the suppression of TEOAE, 2) the amount of suppression of TEOAE varies with the listening effort in active listening condition. Investigating how the listening effort affects the efferent activity provides insight to the descending cortical control of the central auditory system on the periphery.

Subjects and Methods

In the present study, suppression of TEOAE was measured in three listening conditions. In condition 1, the passive listening condition, the suppression of TEOAE was obtained for white noise delivered to the contralateral ear at 60 dB SPL. In condition 2, the active listening condition, spoken words were embedded in the white noise and delivered to the contralateral ear of participants. Each participant was instructed to attend to the words and categorize them as food and animals or animals and vehicles. In condition 3, the passive listening condition, spoken words used in condition 2 were played backwards and embedded in the white noise, and delivered to the contralateral ear. This study design was similar to the method used in the earlier investigation [5].

Participants

Twenty-eight females aged between 18 to 22 years (mean= 20.73 years, standard deviation=1.26) participated in the study. All the participants had normal hearing in both ears with pure-tone thresholds less than 15 dB HL at octave frequencies from 250 Hz to 8,000 Hz. Immittance evaluation revealed normal middle ear functioning in both ears with ipsilateral and contralateral acoustic reflex present at normal levels. None of the participants had any history of otological or gross neurologic deficits, exposure to ototoxic medications or hazardous noise. Participants were informed about the purpose of the study and an informed consent was obtained prior to their participation.

Experimental procedure

Contralateral noise

White noise used in the present study was generated using MATLAB (R2013a, MathWorks, MA, USA) at a sampling rate of 44,100 Hz and 16 bit digital-to-analog converter. Kannada bisyllabic words (belonging to different lexical categories such as food, animals, and vehicle) were used as speech signal in condition 2 (active listening condition) and condition 3. Words were spoken by a female native speaker of Kannada, and digitally recorded using computerized speech lab (CSL model 4150; Hoya Co., Tokyo, Japan) at a sampling rate of 44,100 Hz and 16 bit analog-to-digital converter. Words were embedded into the white noise using MATLAB, the root mean square (RMS) amplitude of white noise was adjusted with reference to the RMS amplitude of speech to obtain at +3, -3, and -9 dB SNRs. To obtain white noise with backward speech, words were reversed using MATLAB and embedded in to the white noise.

Recording of TEOAEs

TEOAEs were recorded using Otodynamics ILO-292 OAE analyser. During recording of TEOAEs, participants were seated comfortably on a reclining chair and TEOAEs were recorded from right ear with and without noise in the contralateral ear. Prior to the suppression of TEOAEs, TEOAE was elicited using nonlinear clicks at 80 dB peSPL, to check for presence of response. Following this, TEOAEs were elicited using linear clicks at 60 dB peSPL, to measure suppression of TEOAE. TEOAEs obtained without noise in the contralateral ear served as baseline. To investigate the effect of listening condition, TEOAEs were recorded in three listening conditions. In condition 1, a passive listening condition, TEOAEs were recorded in the presence of 60 dB SPL white noise in the contralateral ear. In condition 2 and condition 3, TEOAEs were recorded in the presence of white noise with embedded speech in the contralateral ear, at 60 dB SPL. Condition 2 served as active listening condition, where participants were instructed to categorize the words into food and animals or animals and vehicles. This categorization task was similar to that used by an earlier investigation [5]. In this condition, RMS amplitude of noise was adjusted to obtain -3 dB SNR. Here, the SNR of -3 dB SNR was used to compare the findings of present study with the earlier investigation. In condition 3, a passive listening condition, words were played backwards, to make it unintelligible for the listeners, and were embedded in the noise at -3 dB SNR. To investigate the influence of listening effort on the contralateral suppression of TEOAE, TEOAEs were obtained in active listening condition by varying the RMS level of white noise to obtain different SNRs. It comprised of three contralateral noises, in which words were embedded into the white noise at SNRs +3, -3 and -9 dB SNR. These SNRs were obtained by increasing or decreasing the SNR by 6 dB with reference to -3 dB SNR. +3 dB SNR and -9 dB SNR was the most favourable and difficult listening conditions respectively. The contralateral noise was provided at 60 dB SPL.

In active listening condition, categorization task was controlled using Opensesame software v2.8.3 (Available from: http://osdoc.cogsci.nl/) [19] installed on a personal computer. Words from two categories were presented in a random order with an inter-stimulus interval of 2 ms. Participants were instructed to attend to the words and acknowledge by pressing left button or right button of the computer mouse when they heard names of food item or animals and animals or vehicles respectively. Same program was used for presenting contralateral noise in both the passive listening conditions. The contralateral noise was delivered to left ear of the participants using ER-3A insert phones. Finally, a total of eight TEOAE recordings were obtained from each participant (one recording each in condition 1 and condition 3, three recordings in condition 2, and three baseline recordings).

Data analysis

TEOAE data analysis was carried out using EchoMaster 312 [20]. A TEOAE was considered to be present if a response spectral peak was apparent at ≥3 dB above the noise floor for octave frequencies from 1,000 Hz to 4,000 Hz. Three baseline response waveforms were combined to obtain averaged baseline TEOAE. TEOAEs waveforms obtained in the presence of contralateral noise (for each noise condition) was subtracted from the averaged baseline TEOAE waveform, and the difference waveforms were obtained separately for each condition. Using the difference waveforms, the RMS amplitude was calculated for 2 ms segments from 4 to 18 ms.

Results

Effect of active listening on contralateral suppression of TEOAE

Fig. 1A shows overall TEOAE amplitude for baseline, passive and active listening conditions. In the figure it can be

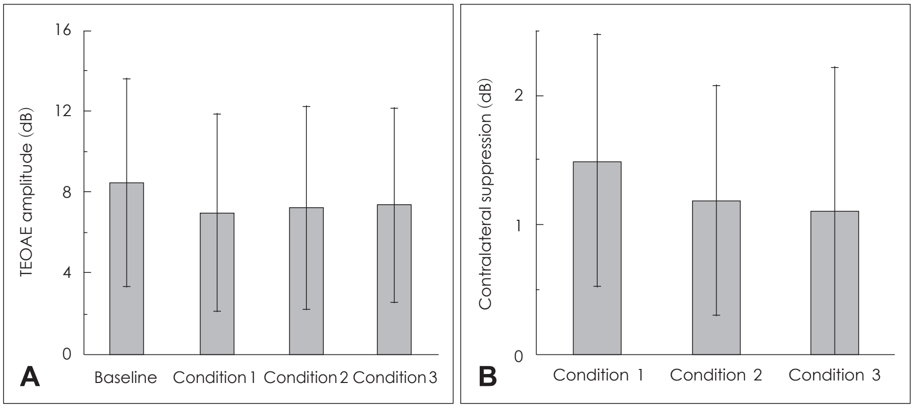

Fig. 1. Mean overall amplitude of TEOAE (A) and mean contralateral suppression of TEOAE (B) across the listening conditions. TEOAE: transient evoked otoacoustic emission.

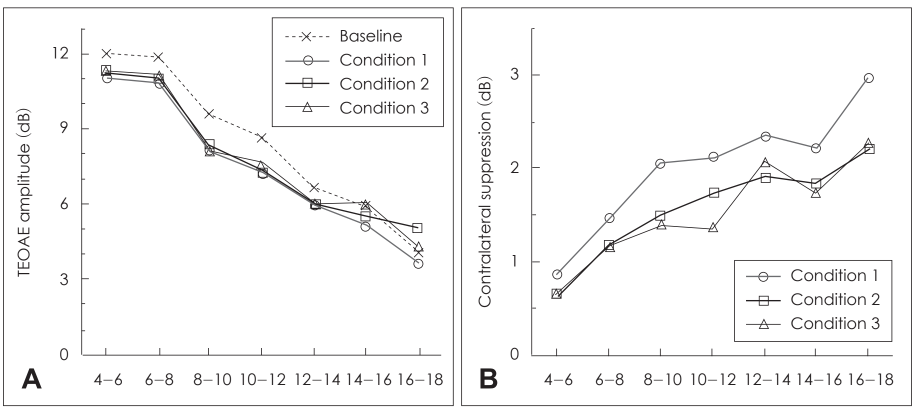

Fig. 2. Mean TEOAE amplitude (A) and mean contralateral suppression of TEOAE (B) across time bands. TEOAE: transient evoked otoacoustic emission.

noted that the mean amplitude is largest for baseline recording and smallest in condition 1. Fig. 1B shows mean contralateral suppression of TEOAE for three contralateral noise conditions. The amount of suppression is largest in condition 1 (for white noise) and smallest in condition 3. To investigate if the mean contralateral suppression is significantly different across the conditions, the data was subjected to repeated measure ANOVA with contralateral noise conditions (condition 1, condition 2, and condition 3) as repeated measures. It showed a significant effect of conditions on mean contralateral suppression of TEOAE [$F(2,54)=5.549$, $p=0.011$]. Pairwise comparison using Bonferroni test revealed that the mean contralateral suppression of TEOAE is significantly different only between two passive listening conditions (condition 1 and condition 3).

Fig. 2 shows TEOAE amplitude across time bands (Fig. 2A) from 4 to 18 ms at an interval of 2 ms. In the figure it can be noted that TEOAE amplitude is largest at earlier time intervals, which corresponds to high frequencies, and it reduced at later time intervals, which corresponds to mid and low frequencies. In addition, across the time intervals, the amplitude of TEOAE is largest for baseline compared to any of the contralateral noise conditions. Further, the amplitude of TEOAE in the presence of noise in the contralateral ear is similar across the contralateral noise conditions. Fig. 2B shows mean contralateral suppression of TEOAE for contralateral noise conditions, across the time bands. From the figure it can be noted that the contralateral suppression is largest in condition 1, while the amount of suppression of TEOAE is similar for condition 2 and condition 3. To investigate if the mean contralateral suppression of TEOAEs are significantly different across the contralateral noise conditions, repeated measure ANOVA was carried out separately for each time bands. The results showed a significant effect of contralateral noise condition on contralateral suppression for all the time bands, except for time intervals 4−6 ms [$F(2,54)=1.339$, $p=0.271$] and 14−16 ms [$F(2,40)=1.794$, $p=0.19$]. Pairwise comparison revealed a significantly larger contralateral suppression for condition 1 compared to condition 3 across the time bands [8−10 ($p=0.015$); 10−12 ($p=0.01$); 12−14 ($p=0.047$); 16−18 ($p=0.042$)] except for time interval 6−8 ms ($p=0.129$), and suppression for condition 1 was significantly different from condition 2 only for time interval 8−10 ms ($p=0.008$) [6−8 (0.134); 10−12 ($p=0.341$); 12−14 ($p=0.089$); 16−18 ($p=0.464$)]. Further, the amount of suppression for conditions 2 and 3 was not significantly different across the time bands [6−8 ($p=1$); 8−10 ($p=1$); 10−12 ($p=1$); 12−14 ($p=1$); 16−18 ($p=0.795$)].

In addition to TEOAE amplitude, level of background noise (noise floor) was also measured in all the contralateral noise conditions. Fig. 3 shows noise floor during recording of TEOAEs in the contralateral noise conditions. In the figure it can be noted that the noise floor is lower in condition 2 (i.e., active listening condition). To investigate if the noise floors were significantly different across the conditions, the noise data was subjected to repeated measure ANOVA. The results showed a significant effect of contralateral noise condition on the noise floor [$F(2,5)=9.96$, $p<0.01$]. Further, pairwise comparison using Bonferroni test revealed that noise floor in condition 2 was significantly lower than that of condition 1 ($p<0.01$) and condition 3 ($p<0.05$).

Effect of listening effort on contralateral suppression of TEOAE

To investigate the effect of listening effort on the contralateral suppression of TEOAE, multiple TEOAEs were recorded in active listening condition with speech in noise at +3, -3, and -9 dB SNR. Fig. 4A shows overall TEOAE amplitude for baseline and various listening effort conditions. It shows that, the mean amplitude of TEOAE is largest for baseline recording and smallest in -3 dB SNR condition. Further, the mean TEOAE amplitudes are similar for +3 and -9 dB SNR conditions. Fig. 4B shows mean contralateral suppression of TEOAE in active listening condition, for contralateral noise with various SNRs (listening effort). The mean suppression was found to be largest in -3 dB SNR, and the amount of suppression was similar for +3 and -9 dB SNR. The data was subjected to further statistical analysis using repeated measure ANOVA with SNR as within subject variable. It showed a significant effect of SNR on the contralateral suppression of TEOAE [$F(2,54)=6.5$, $p=0.003$]. Bonferroni test revealed the amount of contralateral suppression to be significantly different across the SNR conditions [+3 and -3 SNR ($p=0.038$); -3 and -9 SNR ($p=0.013$)], except for SNR between +3 and -9 dB ($p=1$).

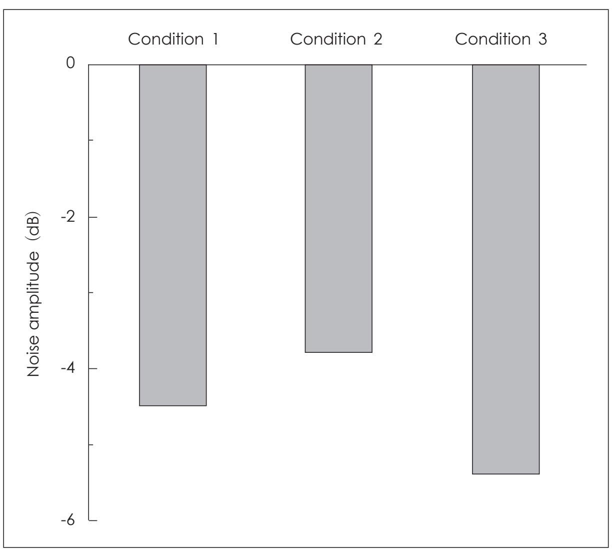

Fig. 3. Mean noise level (noise floor) across the listening conditions.

Fig. 5A shows TEOAE amplitude across time bands from 4 to 18 ms for various listening effort conditions. The figure shows that, across the time bands, the amplitude of TEOAE is largest for baseline recording and smallest in +3 dB SNR condition. Fig. 5B shows mean contralateral suppression of TEOAE across time bands for different SNR conditions. In the figure it can be noted that the amount of suppression is largest for -3 dB SNR condition, across the time bands. While the amount of suppression is similar for +3 and -9 dB SNR conditions. Repeated measure ANOVA with SNR as repeated measures revealed no significant difference for mean contralateral suppression between the conditions across the time bands {4−6 [$F(2,54)=0.521$, $p=0.597$]; 8−10 [$F(2,54)=2.139$, $p=0.128$]; 10−12 [$F(2,50)=2.314$, $p=0.109$]; 12−14 [$F(2,48)=2.091$, $p=0.135$]; 14−16 [$F(2,38)=1.081$, $p=0.349$]; 16−18 [$F(2,34)=1.788$, $p=0.183$]}, except for time interval 6−8 ms [$F(2,54)=5.27$, $p=0.013$].

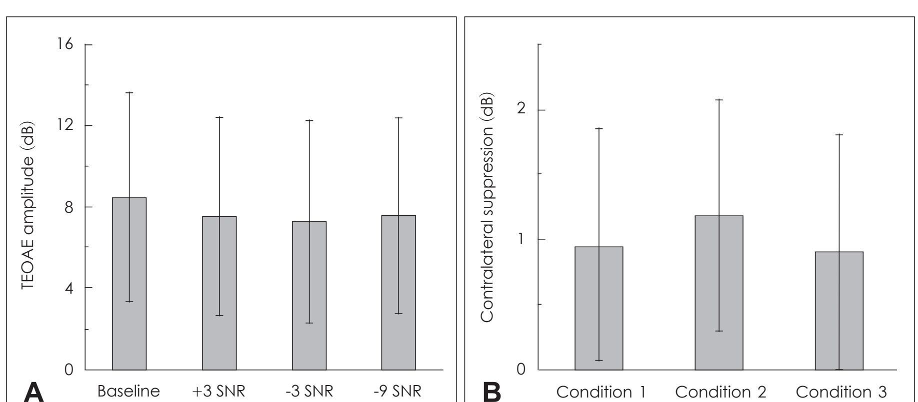

Fig. 4. Mean overall amplitude of TEOAE (A) and mean contra-lateral suppression of TEOAE (B) in active listening condition across the SNRs. TEOAE: transient evoked otoacoustic emission, SNR: signal-to-noise ratio.

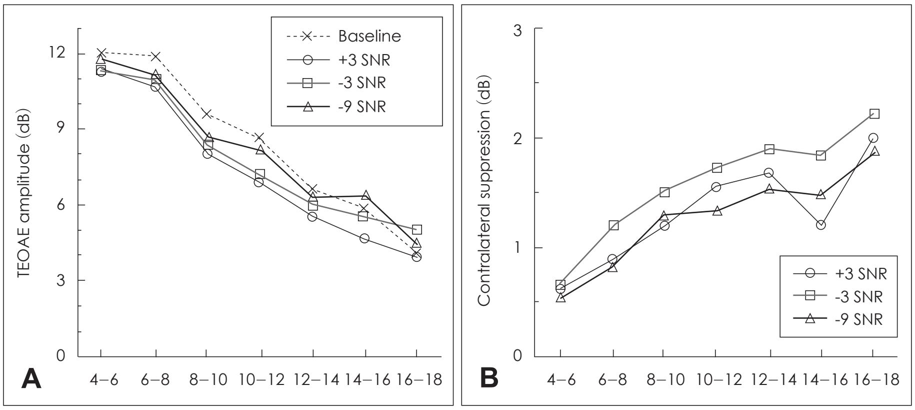

Fig. 5. Mean TEOAE amplitude (A) and mean contralateral suppression of TEOAE (B) across time bands in active listening condition across the signal-to-noise ratios. TEOAE: transient evoked otoacoustic emission.

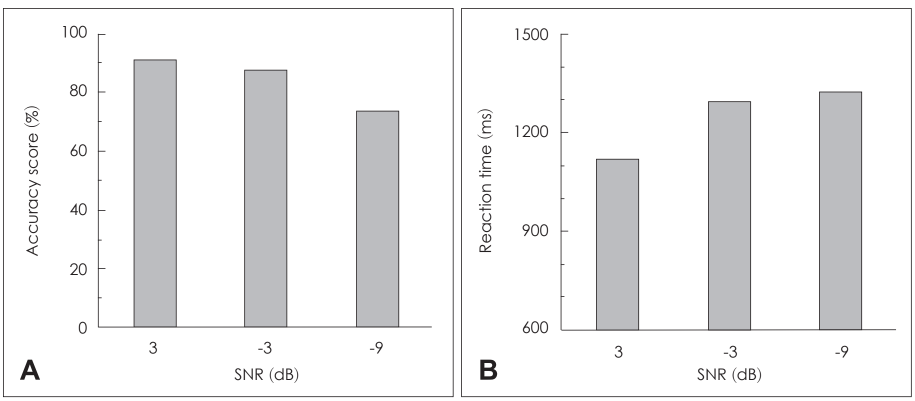

Fig. 6. (A) Shows the percentage of correct response and (B) shows mean reaction time for +3, -3, and -9 dB SNR. SNR: signal-to-noise ratio.

Accuracy score and reaction time for categorization task in active listening condition is shown in of Fig. 6 respectively. Fig. 6A, it can be noted that, the accuracy score is highest in favorable listening condition (+3 dB SNR), and it decreased with reduction in SNRs. Further, in Fig. 6B it can be observed that, the reaction time for correct categorization of words is shortest in for +3 dB SNR, and it increased with reduction in SNRs. To investigate if the mean reaction times and accuracy scores are significantly different across the SNRs, the data was analyzed using repeated measures of ANOVA and post-hoc analysis was done using Bonferroni test. It showed a significant effect of SNR on reaction time [$F(2,48)=7.49$, $p<0.01$] and accuracy score [$F(2,48)=80.088$, $p<0.01$].

Discussion

Role of active listening on suppression of TEOAEs

The present study investigated the influence of active listening and listening effort on the contralateral suppression of TEOAE. It shows that, the overall amplitude of TEOAE is largest in baseline condition and it reduced in the presence of noise in the contralateral ear, in line with earlier reports. [5,10,21] Further, it was also observed in the current study that the contralateral suppression of TEOAE was largest for condition 1 (white noise) compared to active listening condition. This finding in the present study was not expected and deviates from the earlier investigation [5], which has shown greater suppression in active listening condition. However, the amount of suppression during active listening, in condition 2, was greater than the amount of suppression obtained during passive listening in condition 3. This finding is similar to the results obtained in earlier investigation, suggesting that active listening has an influence on the efferent activity. Further, time band analysis showed least contralateral suppression for earlier time bands (which corresponds to high frequency), and largest suppression for later bands (corresponds to mid and low frequencies), which is in consonance with earlier investigations [5]. Comparison of contralateral suppression of TEOAE between the listening conditions showed largest suppression for condition 1 for all the time bands, which was not expected. In addition, results of the present study also showed a significantly lower noise floor for condition 2 (active listening) compared to other conditions, comparable to the results established by several investigators [13,22,23]. Lower noise floor could be attributed to the efferent activity associated with the attentional demands of the behavioural tasks [23]. Another possible reason for lower noise floor is that when attending to auditory stimuli, listener might attempt to control physiological noise by limiting motion and controlling breathing [11].

The contrasting finding obtained in the present study, may be attributed to the methodological differences between the investigations [1]. In the present study, the level of noise was adjusted with reference to the level of speech to obtain desired SNRs. In contrast, Garinis, et al. [5] adjusted the level of speech with reference to the RMS level of noise. In the present study, contralateral noises (white noise and white noise with embedded speech) were delivered at 60 dB SPL. While on the other hand, the level of white noise in Garinis, et al. [5] study was fixed at 60 dB SPL in both white noise alone and white noise with embedded speech conditions. Here, it could be possible that, in the present study, the levels of white noise are slightly different in noise alone and noise with embedded speech conditions [2]. In the present study the words were presented at an interval of 2,000 ms, while in the Garinis, et al. [5] study words were presented at an interval of 1,500 ms. Compared to Garinis, et al. [5], in the present study words were presented at a slower rate, this might have resulted in lower demand from the participants for the categorization task. Further, longer interval between the words could have resulted in occurrence of multiple passive listening events, when participants are not expecting the words, during recording of OAEs. Thus, both lower demand and events of passive listening conditions might have resulted in different results across the investigations [3]. In addition, Garinis, et al. [5] included participants with large amplitude TEOAEs for their investigation, while in the present study such strict criteria was not used for selection of the participants. These methodological differences between investigations could have resulted in contrasting findings.

Similar to the contrasting findings noted in the present study, investigations to understand the effects of attention on the suppression of OAEs have also reported contrasting findings, in terms of the direction and type of effects [10,11,21,24]. Several studies have reported a significant reduction in the suppression of OAE, when attention was directed to the ipsilateral ear [10] and contralateral ear [11,21]. In contrast, Maison, et al. [24] reported a significant increase in the contralateral suppression of TEOAE when attention was focused to the contralateral ear. Discrepancies in the findings, on the influence of attention on the contralateral suppression of TEOAEs, has been attributed to methodological differences across the investigations. To conclude, similar to the findings of investigations measuring effect of attention, listening conditions may also have contrasting effects on contralateral suppression based on direction and type of effects.

Role of listening effort on suppression of TEOAEs

The present study also investigated the effect of listening effort on the contralateral suppression of TEOAEs. SNR has an effect on listening effort and it is found that listening effort is low in favourable listening conditions, while it increases with reduction in the SNR (or less favourable listening conditions) [17,18]. Hence, in the present study the SNR of the contralateral noise stimulus was varied from +3 to -9 dB SNR in steps of 6 dB and TEOAEs were recorded. Analysis of accuracy scores and reaction time for correct categorization of words showed least errors and shorter reaction time at +3 dB SNR, while the accuracy scores reduced and reaction time increased with reduction in the SNR. Reduction in accuracy scores with SNR indicates that the task difficulty increased with reduction in the SNR. Increased reaction time at reduced SNRs, could be attributed to the increased listening effort when identifying words in unfavourable listening conditions. Further, the results showed significantly larger suppression for -3 dB SNR, while the amount of suppression for +3 dB and -9 dB SNR was similar. Here, it was expected that the amount of contralateral suppression of TEOAE would increase with the listening effort. As expected, there was an increase in the amount of suppression when the SNR was decreased from +3 dB to -3 dB SNR. But, further reduction in the SNR did not result in further increase in amount of suppression, rather the amount of suppression decreased compared to -3 dB SNR. Currently, it is not clear as to why there was a reduction in amount of suppression at -9 dB SNR. It may be speculated that the involvement and benefit of MOC mediated mechanisms in speech-in-noise perception to be dependent on task or stimuli/noise [25]. Hence, there is a need for further research to better understand the role of listening effort on the suppression of TEOAEs.

In conclusion, the findings of the present study shows no effect of active listening on the contralateral suppression of TEOAEs. Although the present study shows no effect of listening conditions, the influence of active listening on suppression of TEOAE cannot be ruled out. In addition, the present study revealed a significant effect of listening effort in the active listening condition on the contralateral suppression of TEOAEs.

Conflicts of interest

The authors have no financial conflicts of interest.

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