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Original Article

Effect of Musical Experience on Cochlear Frequency Resolution: An Estimation of PTCs, DLF and SOAEs

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BACKGROUND: There is a lot of debate on whether musical experience/training can affect cochlear filter characteristics and thereby enhance frequency resolution skills in musicians (Ms). Thus, the objective of the study was to compare between Ms and non-musicians (NMs) and correlate the frequency resolution skills with years of musical experience, the difference limen for frequency (DLF), and the Q10 values of psychophysical tuning curves (PTCs) measured at 2 characteristic frequencies (CFs), 1000 and 4000 Hz. The secondary objective was to find out whether spontaneous otoacoustic emissions (SOAEs) can be recorded among Ms more frequently than among NMs.

METHODS: Thirty-six listeners with normal hearing participated in the study. They were 18 Ms with a minimum of 8 years of musical experience, and 18 NMs. Forward-masked PTCs and DLF tests were assessed for each listener in the right ear at 2 CFs, 1 and 4 kHz, and SOAEs were measured using standard protocol.

RESULTS: The results obtained indicated that values of the psychophysical measures, DLF and Q10, were better among the Ms group. Statistically significant differences were seen when measurements were done at 1 KHz and 4 KHz. SOAEs were recorded in a higher number of Ms than NMs. Musical experience had a moderate positive correlation with PTC Q10 values at both 1 and 4 kHz, but not DLF values.

CONCLUSION: This study indicates that musical experience enhances peripheral filtering, and thereby betters cochlear frequency selectivity in Ms.

KEYWORDS: Frequency selectivity, musicianship, cochlear filtering, psychophysical tuning curve, pitch perception

INTRODUCTION

Musicians (Ms) are a specialized group of listeners, as music writing or performing involves such intricate elements like pitch and rhythm, where a single off-tune note can make a huge difference. Earlier researches show that Ms display extraordinary pitch perception skills at both cortical and sub-cortical levels. Electrophysiological studies have largely concluded higher pitch-coding ability among Ms.[1-5] However, these experience-dependent enhancements could also possibly be at the level of the cochlea, as it is the first structure to influence the sound in terms of frequency resolution, thus partially accounting for pitch perception.[6] Another possibility could be enhanced efferent feedback by the medial olivocochlear system (MOC) due to musical training.[7-10] There are physiological measurements, such as stimulus-frequency otoacoustic emissions (SFOAEs), directly aiming to capture musical influence on cochlear activity, which report Ms to have enhanced SFOAE amplitudes compared to non-musicians (NMs).[11] However, comparison studies evaluating frequency selectivity at the peripheral level between Ms and NMs in the Western as well as the Indian scenario are very few. They usually incorporate behavioral measurements of pitch or rhythm identification, or psychophysical measures such as difference limen for frequency (DLF) and psychophysical tuning curves (PTCs). Ms have been reported to have lower DLF scores than NM.[12-15] However, PTCs have shown mixed results. In a few studies, PTCs showed significant differences, where Ms had better Q10 values than NMs when measured at 4 kHz characteristic frequency (CF),[16,17] or at more than 2 CFs.[18] Other literatures have shown no difference at any of the CFs.[19,20] Thus, the question still remains whether cochlear mechanisms contribute toward better pitch perception in Ms. Moreover, there are no studies for PTCs among Ms trained in Indian classical music. Ms also differ in terms of training method received, especially musical scale training, ear training, and structure of training.

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Need for the Study

Few studies have probed the perceptual benefits in Ms due to peripheral filtering. Moreover, research in the last decade has remained equivocal on this issue, largely due to difficulty in carrying out studies among a large number of subjects, the method of psychophysical measurement being particularly difficult to repeat, and other such methodological issues. Hence, there is a strong need to gather data on different sets of Ms in order to understand Ms' and NMs' ability or performance on pitch measures and their cochlear frequency selectivity skills.

Aim of the Study

The aim of the present study is to compare frequency selectivity skills between Ms and NMs.

The objectives include:

- Comparing the 2 groups for frequency discrimination using DLF;
- Comparing the 2 groups for cochlear tuning using PTCs measured at 2 CFs; and
- Comparing the 2 groups for presence of SOAEs and correlating them with PTC Q10 values.

METHOD

Participants

Eighteen participants, including vocalists and instrumentalists, who had been Ms from a young age and who were in the age range of 22-33 years, were recruited for the study. Their mean age was 25.3years (SD: 2.98 years). Further, another group of subjects, NMs who were age-matched to the musician group, were recruited as the control group. They had no formal training in music nor did they practice singing/play an instrument as a hobby. Their mean age was 24.1 years (SD: 2.33 years). All participants had normal hearing sensitivity (thresholds $\leq$20 dB HL; 250-8000 Hz for both AC and BC) with no history of middle-ear, neurological, or psychological abnormality. The Ms had a minimum of 8 years of musical experience and acknowledged $\geq$ 1 hour of practice daily with their instrument or voice.

MAIN POINTS

- This study explores the effect of learning music on behavioral measures of frequency selectivity, using PTCs and DLF. While information on cortical and brainstem electrophysiological measures are available, there is a lack of information on measures that-check cochlear filtering process. Therefore, the present study was undertaken.
- The results of DLF revealed that Ms significantly outperformed NMs by almost 4-5-fold.
- The *Q*10 values, a measure of PTCs, were also better for Ms than NMs. This was true for both frequencies tested, 1 kHz and 4 kHz. Earlier studies had shown that only *Q*10 measured at 4 kHz showed the effect of musical training.
- SOAEs were recorded in a greater number of Ms than NMs, the significance of which is unknown at the moment.
- Frequency resolution ability at cochlea as measured by behavioral measures is better among Ms. This may have a bearing on their enhanced pitch perception.

Instrumentation

Air-conduction hearing thresholds were measured with a calibrated clinical audiometer MAICO MA-53 with TDH 49 Earphones with MX-41/AR ear cushions, and bone conduction (BC) was measured using B-71 Radioear bone vibrator. Immittance audiometry was done with AmpliVox middle-ear analyzer. Spontaneous otoacoustic emissions (SOAEs) and transient evoked otoacoustic emissions (TEOAEs) were measured via standard protocol provided by Neuro-Audio software (v.2010) in an HP laptop with Windows 8 processing system via standard foam ear tips. DLF was measured using MLP software in MATLAB (The MathWorks, Natick, MA).[21] For PTCs, custom-built coding was done in MATLAB, in a Lenovo Z580 laptop with Windows 7 processing system. The output was routed through a Focusrite Scarlett 2i2 soundcard (Focusrite Scarlett 2i2, 2nd Gen Audio Interface) and delivered monoaurally to the right earphone of a Sennheiser HD180 headset.

Procedure

All tests were carried out in a sound-treated room with noise levels within the permissible limits (ANSI S3.1-1999).[22] All the participants answered a self-administered questionnaire pertaining to their musical history, including age at commencement of their musical training, years of musical experience, their primary and secondary instruments and how they tune them, handedness, their hearing health, noise exposure, hearing loss or tinnitus complaints, and also their usage of antibiotics, drugs, alcohol, or smoking. Otoscopy was performed to rule out confounding factors impacting the ear canal or tympanic membrane. Air-conduction (AC) hearing thresholds were measured at octave frequencies from 250 Hz to 8000 Hz via Modified Hughson and Westlake procedures using a 5 dB step size. Bone conduction (BC) thresholds were measured for 250 Hz, 1 kHz, and 4 kHz. Immittance audiometry was done with 226 Hz probe tone, and ipsilateral and contralateral acoustic reflex thresholds were also measured for all the participants. TEOAEs were measured in order to know the intactness of cochlear micro physiology and to rule out NIHL. Furthermore, an online hearing test, called the tone-deaf test, was done and all were screened for tone deafness including NMs.[23] All the participants cleared the prerequisites; post which, psychophysical measurements such as DLF and forward-masked PTCs were done. Lastly, SOAE's were measured objectively to measure frequency tuning for the cochlea. The following is the protocol used for each test:

Psychophysical Tuning Curves (PTC)

Frequency selectivity of the auditory system was assessed for each listener in the right ear at 2 CFs of 1 and 4 kHz using the forward-masking paradigm presented, in a 3-interval, forced-choice task. These CFs were chosen based on a previous study,[24] to avoid difficulties with short-duration tones at lower frequencies where signal bandwidth can exceed that of the filter.

Stimuli

The masker was a 300 ms pure-tone gated with 5 ms cos square ramps, and masker bandwidth was kept as 80 Hz. Tonal maskers had normalized frequencies of 0.12, 0.25, 0.50, 0.62, 0.75, 0.87, 1.00, 1.05, 1.12, 1.25, and 1.50 relative to the probe's CF. The masker was followed immediately by a contiguous probe tone (0-ms masker–probe offset). Probe signals were brief (35 ms, 10 ms ramps) sinusoidal tones (1 or 4 kHz), presented at a fixed low-level intensity (20 dB SL of listeners' threshold at CF which was measured by estimating the absolute threshold at that frequency in the psychoacoustics toolbox in MATLAB) as the appropriate probe level is of specific interest when determining PTCs. Each trial consisted of a masker–probe tone combination. A high-pass noise (cutoff frequency: 1.2*CF Hz) was presented at a low intensity (−50 dB spectrum level re probe) concurrent with the masker–probe stimuli to limit off-frequency listening effects. The test paradigm selected here is closer to the paradigm used in Bidelman G, Schug J, Jennings S, and Bhagat S (2014).[16]

Procedure

Listeners sat comfortably on a chair in a sound-proofed booth. Masked thresholds were measured adaptively by varying the level of the masker with the probe fixed at 20 dB SL. A fixed-signal method is preferable to a fixed-masker level (i.e., adaptively varying probe level) as it provides a more accurate depiction of auditory filter shape. Based on the first few observations, the normalized frequencies far from 1.00 or CF were chosen first for the participant to understand the task, as it provided a less difficult situation, better detection of probe tone, and better performance achievement. On each trial, participants heard 3 sequential intervals, 2 of which contained only the masker, and 1 which contained the masker and probe (assigned randomly). Listeners were required to identify the interval containing the probe. Responses were made verbally indicating the number of the interval containing the probe, for example, 1, 2, or 3. Each interval was separated by a 400 ms interstimulus interval (ISI). Masked thresholds were measured using a step size of 5 dB for 4 reversals and 2 dB for 8 reversals, where the geometric means of the last 8/12 reversals were used to compute each listener's masked threshold. A single masked threshold was obtained for each of the 11 masker–probe combinations and used to construct a listener's PTC at a given CF. Brief task familiarization was provided only once, to obtain forward-masked PTCs with minimal learning effects.

Response analysis

PTCs were interpreted by measuring the quality (Q_{10}) factor of the auditory filter. Q_{10} is a normalized measure of filter sharpness and was used to quantify frequency tuning for each listener. Q10 was computed via a custom-built coding done in MATLAB software using the formula Q10 = tip_f/bw, where bandwidth (bw) is calculated at 10 dB above tip frequency. Lastly, Q10 values were tabulated for both Ms and NMs in Microsoft Windows EXCEL spreadsheet for data analysis and comparison.

Difference Limens for Frequency (DLF)

The pitch discrimination task was tested for 1000 Hz and 4000 Hz tone in a 3-interval forced-choice task presented for each listener in their right ear.

Stimuli

The pitch discrimination task was carried out using the maximum likelihood procedure (MLP) in MATLAB 2014, which uses 250 ms-long pure tones with standard tones being 1000 Hz or 4000 Hz as the chosen and variable tone at different frequencies, to arrive at the frequency difference between them. Stimuli were pure tones with onset and offset gated with 2 10-ms raised cosine ramps and presented at 40 dB SL for all participants.

Instruction

The participants were asked to tell the temporal position (i.e., 1, 2, or 3) of the tone which was heard different than the other 2 in terms of pitch.

Procedure

The pure-tone pitch discrimination task was carried out using the MLP.[21] The MLP incorporates a large number of candidate psychometric functions, and after each trial it calculates the probability of obtaining the listener's response to all of the stimuli that were presented given each psychometric function. The psychometric function yielding the highest probability is used to determine the stimulus to be presented on the next trial. Within about 12 trials, the MLP usually converges on a reasonably stable estimate of the most likely psychometric function, which then can be used to estimate threshold.[25] Stimuli were recorded at a sampling rate of 44 100 Hz. A 3-interval forced-choice method using an MLP was employed to track an 80% correct response criterion. Randomized positions of standard and variable signals were set accordingly. During each trial, stimuli were presented in each of the 3 intervals: One interval contained the standard stimulus and the other 2 intervals had the variable stimulus. The participants had to discriminate the highest pitch tone among a number of choices or detect the different tones of all. Subjects were given one practice trial before the commencement of the test.

Synchronized Spontaneous Otoacoustic Emissions (SSOAEs)

SOAEs were collected in the frequency range of 1000 Hz to 5000 Hz with a stimulus rate of 11 Hz and stimulus intensity at 70 dB SPL. The filter settings were 500 to 10 000 Hz, and a maximum of 300 sweeps were averaged. The response was analyzed in a window of 80 ms after the evoked part of the response had faded away with zero stimulus artifacts after 20 ms. An ear was classified as "with SOAES" when at least 2 long-lasting peaks exceeding the noise floor by 3 dB were found in the SSOAE spectrum. Thus, a response with SNR of ≥ 3 dB at any 2 frequencies was taken as "present" for that ear in our study, and was noted in a Microsoft Windows EXCEL spreadsheet.

RESULTS

The present study aimed to examine the differences in cochlear frequency selectivity skills between Ms and NMs. The results were computed for DLF, PTCs, and SOAEs, where data were analyzed using the IBM Statistical Package for the Social Sciences (SPSS) software. The results are discussed for each of the tests separately.

Difference Limens for Frequency (DLF)

The mean DLF score obtained for pure tones for the musician group at 1000 Hz was 7.15 (±3.40) and for 4000 Hz was 24.94 (±7.40). For NMs, the mean DLF score at 1000 Hz was 31.28 (±15.54) and for 4000 Hz was 76.01 (±34.03). DLF scores obtained among Ms were lower than among NMs for both 1000 Hz and 4000 Hz. The DLF scores measured at 4000 Hz were higher than the scores obtained at 1000 Hz. This trend was seen for both the groups, and the group differences were larger for 4000 Hz as well. The group difference in mean values

Table 1. Mean and Standard Deviation Scores for Q10 Values of PTCs

	Q10 1000 Hz	Q10 4000 Hz
Musicians		
Mean	11.35	17.05
Standard deviation	2.03	2.59
Non-musicians		
Mean	7.61	12.65
Standard deviation	1.17	2.96

was significant [$F(4930.645,1)=41.299$, $P < 0.05$] at 1000 Hz and [$F(22090.467,1)=38.626$, $P < 0.05$] at 4000 Hz.

PTC

The mean Q10 value for the musician group at 1000 Hz is 11.35 (±2.03) and for 4000 Hz is 17.05 (±2.59). For NMs, mean Q10 score at 1000 Hz was 7.61 (±1.17) and for 4000 Hz was 12.65 (±2.96), as mentioned in Table 1.

Ms showed higher Q10 values than NMs for both 1000 Hz and 4000 Hz CFs. The Q10 value was higher for both the groups at 4000 Hz than at 1000 Hz. The difference between the 2 groups was significant [$F\,(118.117,1)=41.684$, $P < 0.05$] at 1000 Hz and [$F\,(163.739,1)=21.243$, $P < 0.05$] at 4000 Hz.

In addition, Spearman's rank correlation test was done separately for Ms and NMs, to compare each musician's PTCs and DLF values. It showed no correlation [$r=-0.328$, $P > 0.05$] between Q10 values of PTC and DLF for 1 kHz, but moderate correlation [$r=-0.579$, $P < 0.01$] was found at 4 kHz for the Ms group. There was no significant correlation for PTCs and DLF scores among NMs at 1 kHz [$r=-0.464$, $P > 0.05$] as well as 4 kHz [$r = -0.318$, $P > 0.05$].

Spontaneous Otoacoustic Emissions (SOAEs)

Studies have shown that SOAEs have the same mechanism responsible as frequency selectivity in PTCs—active cochlear mechanisms. Thus, SOAEs were recorded for both the ears in all the participants, from 1 kHz to 5 kHz, and SNRs were noted. Table 2 shows the number of participants having presence or absence of SOAEs in both the groups. The criteria for present/pass SOAEs was taken as SNR of ≥3 dB, consistent with the findings from the R.R. Baiduc, Jungmee Lee and Dhar study (2013), at any 2 frequencies or more from the frequencies measured.[26]

Table 2. Number of Musician and Non-Musician Participants Having Present/Absent SOAEs

	Present SOAEs (No. of Participants)		Absent SOAEs (No. of Participants)	
	Right	Left	Right	Left
Musicians ($N=18$)	9	9	9	9
NMs ($N=16$)	2	3	14	13

The results revealed that 50% of total Ms had SOAEs present when tested in both the right and left ears. As for NMs, only 12.5% had SOAEs present in the right ear and 18.75% had SOAEs present in the left ear. Chi square test was done to know the difference between presence and absence of SOAEs between Ms and NMs. The test results showed that the number of subjects showing the presence of SOAEs in the right ear was significantly more among Ms than NMs, but for the left ear, the *P* value obtained was 0.057, showing no difference.

Effect of Years of Musical Experience DLF & PTC Q10 Values

Spearman's rank correlation was done to assess the effect of years of musical experience on DLF & PTC Q10 values. The results, as mentioned in the Table 3, show moderate negative correlation [$r=-0.471$, $P < .05$] of years of musical experience with DLF at 4 kHz but not at 1 kHz. There is also a moderate positive correlation [$r=-0.464$, $P < .05$] for PTC Q10 values at 1 kHz and 4 kHz [$r=-0.513$, $P < .05$].

Thus, the results reveal a significant effect of the number of years of musical experience on both DLF and PTCs. Significant negative correlation for DLF and musical experience at 4 kHz reveals that with increasing years of musical experience, DLF values tend to become lower, and the significant positive correlation for PTC with musical experience shows that with increase in the number of of years of musical experience, there's also an increase in the PTC Q10 values for both the frequencies.

DISCUSSION

In the present study, the frequency resolution skills of Ms were compared with NMs via tests like DLF, PTCs, and SOAEs. The results of statistical analysis showed that Ms have significantly lower average DLF scores than NMs at both the frequencies (1000 Hz and 4000 Hz) considered for the study. The lower scores indicate better frequency discrimination. DLF values are seen to be higher in our study than previous studies, which could be attributed to less number of practice trials for NMs, as Kishon-Rabin L, Amir O, Vexler Y, and Zaltz Y (2001) reported, that practice trials have an effect on DLF scores and could result in NMs also getting smaller DLF values.[14] It would also appear from the current results that Ms outperformed NMs with scores that were better by almost 4-5-fold at both the frequencies, which echoed with previous literature.[2,13] The DLF scores, when correlated with years of musical experience, as mentioned in Table 3, showed that with more musical experience, DLF scores for 4 kHz decreased, suggesting that longer duration of musical training/experience results in better frequency discrimination skills, which is in line with previous literature.[14,27] However, this was a moderate correlation. Further, this test does not comment on cochlear frequency selectivity alone. However, it validates previous results that Ms have better frequency

Table 3. Spearman's Rank Correlation and Significance Value for DLF & PTC at 1000 Hz and 4000 Hz in Association with Musical Experience

Characteristic Frequency	DLF		PTC Q10 values	
	Spearman's Rank Correlation Value (*r*)	Sig.	Spearman's Rank Correlation Value (*r*)	Sig.
1000 Hz	−0.433	0.064	0.464	0.045
4000 Hz	−0.471	0.042	0.513	0.025

discrimination skills than NMs. It also might be one of those studies with more stringent criteria, but still showing such large differences in DLF values between Ms and NMs.

For this study, forward-masked PTCs were chosen instead of simultaneous masking, as they are known to fetch sharper tuning curves.[16,28] Our study paradigm was consistent with the previous studies in terms of probe, signal of duration of 35 ms and fixed intensity of 20 dB SL, normalized frequencies of tonal maskers, and 2 CFs of 1 and 4 kHz.[16] This study chose the inclusion criteria of Ms a little differently, as the experimental group included both professionally trained and self -taught Ms who were equally experienced, which violates the definition of a "musician" given in previous studies, being the ones having received formal training only. The results of statistical analysis for PTCs showed Ms having significantly higher average Q10 values for forward-masked PTCs than NMs, at both the frequencies. The higher the score, the sharper the auditory filter at that frequency or better the cochlear frequency selectivity skills. This is a strong evidence of musicianship enhancing peripheral cochlear filtering, thereby increasing cochlear spectral resolution in an experience-dependent manner. However, it is also in contrast with findings of a few studies stating no significant difference for 1 kHz CF,[16] or no difference at all.[19] Moreover, the overall scores for Ms and NMs for both the frequencies were observed to be better than previous studies.[16,18] This could have been due to usage of the forward-masked PTCs paradigm, or that PTCs could have been positively affected in the vicinity of SOAEs. In addition, motor responses, in order to respond for PTCs, were pressed by a third person and not the subjects themselves, as they would have had a very short, quick release of the spacebar whenever they detected a probe tone,[19] which might be more of a motor reflex than a thoughtful response. Thus verbal responses were considered over motor responses.

It was also noted that although Ms showed sharper tuning curves than NMs for both the frequencies, Q10 values were higher at 4 kHz than 1 kHz CF, which might be due to higher cochlear amplification or a suppression of non-linearity effect at higher frequencies. It could also be because of the fact that physiologically, MOC fibers are denser at the basal end of the cochlea,[29] therefore more modulatory gain would be provided leading to better resolution at 4 kHz.[30]

The years of musical experience were also positively correlated with PTC Q10 values. Statistical results showed a moderate positive correlation at both the frequencies, indicating that the more the musical experience, the better the frequency selectivity of cochlea.

Furthermore, SOAEs are a direct measure of cochlear activity, which is shown to be associated with specialized listeners, though even people with normal hearing may not have its presence. The pass criteria or presence of SOAE were taken as SNR of $\geq$3 dB, which is consistent with previous studies.[26] However, SOAEs could have been taken as present, specifically for each frequency. Ms showed significantly higher probability of SOAEs being present than NMs, when compared in the right ears. The results obtained in this study showed significant difference between Ms and NMs having present SOAEs, for right ear. Even though 50% of Ms showed SOAE presence, when compared with 18.75% of NMs showing its presence for their left ears, this difference couldn't reach a .05 level of significance.

Further, there was significant difference in years of musical experience which showed moderate negative correlation for DLF at 4 kHz but not at 1 kHz, suggesting that DLF values decrease with increase in the number. of years of musical experience. There was also a moderate positive correlation for the PTC Q10 values for both 1 and 4 kHz, suggesting an increase in Q10 values with an increasing number years of musical experience.

Hence, the present study indicates that cochlear frequency tuning is sharper in Ms when compared to NMs, as PTC Q10 values were higher in Ms at both the CFs chosen. The frequency discrimination skills assessed by DLF also showed better performance, with Ms having about 4-5-fold lower DLFs than NMs at both the frequencies. The current study also showed Ms having more participants with presence of SOAEs than NMs, further supporting the fact that Ms might have more active mechanisms pertaining to cochlea than NMs. The number of years of musical experience also influenced the enhancement of frequency resolution skills in Ms.

CONCLUSION

Frequency resolution is fundamental to speech perception and music perception. It aids non-Ms in coarse perceptual processes like listening to speech in degraded conditions, as well as Ms in their finer aspects of melody and harmony. This study is one of the few which have explored the cochlear aspects of fine-pitch perception in Ms. Our results strongly support the view that musical training enhances peripheral filtering, thereby leading to better frequency resolution skills in Ms.

Ethics Committee Approval: Ethical clearance was obtained from the in-house ethical committee of Samvaad Institute of Speech and Hearing.

Informed Consent: All participants gave their informed consent prior to the administration of the study.

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