*Int. Adv. Otol. 2009; 5:(2) 195-202*

ORIGINAL ARTICLE

# Hearing Characteristics and Frequency Discrimination Ability in Musicians and Nonmusicians

**Ozgul Akin, Erol Belgin**

*Cukurova University ENT Dept. - Audiology and Speech Pathology Section, (OA) Adana, Turkey*
*Hacettepe University Audiology and Speech Pathology Department, (EB) Ankara, Turkey*

**Objective:** Difference limen for frequency (DLF) is the smallest detectable change in frequency. The perception ability of this difference changes from person to person depending on the level of musical education. It is mainly mentioned on the studies about DLF that musical education has an improving effect on the perception of frequency discrimination. Thus the aim of this study was to determine the effect of formal music education on the performance of frequency discrimination and hearing sensitivities.

**Materials and Methods:** In this study a total of 32 individuals aged between 19 and 28 years were tested in two groups. The first group was made up of musically untrained participants and the second group consisted of musically trained individuals. Primarily data from DLF test and the pure tone thresholds were compared among groups. The performance of frequency discrimination changing from sensation level and frequency was also studied by using FMDL procedure.

**Results:** The results indicated that the musically trained participants performed better than untrained participants in frequency discrimination tasks. It was found that the frequency discrimination ability increases in the 500-4000 Hz frequency range and with a higher sensation level for all participants.

**Conclusions:** Studies using these techniques can provide information regarding music education influences auditory perception. Musical training might increase the spontaneous attention to the sound heard and the ability to discriminate. Music becomes a useful tool with which to motivate and enliven the sessions.

*Submitted : 28 July 2008* *Revised : 30 December 2008* *Accepted : 11 February 2008*

Hearing is an important aspect of communication and provides a pleasurable experience to people specially listening to music [1, 2]. Over the past 20 years, there has been an increasing, worldwide research interest of musical education, effect of musical training on auditory skills [1-7]. Particular studies in audiology have focused on musical perception and hearing sensitivity [8-10]. It is expected that musicians, in general, will be proficient in auditory modality, because of their extensive experience with auditory input. Musicians acquire a great expertise in processing auditory features like tonal pitch or timbre. [8, 9, 11].

In psychophysics, a just noticeable difference is the smallest difference in a specified modality of sensory input that is detectable by a human being. It is also known as the difference limen or the differential threshold [12-14]. Difference Limen (DL) is the smallest difference which can be discriminated between two stimuli or one which is barely above the threshold. Studies examined the frequency discrimination ability focused on how the ears processed difference limen for frequency [15, 16].

In acoustic hearing, difference limens for frequency modulation (FM) have also been studied extensively[3,17,18]. Frequency modulation (FM) conveys information over a carrier wave by varying its frequency. Frequency modulations are abundant in speech, music and other sounds that are available in environment.

The first method to evaluate frequency discrimination performance is the determination of two tones that are

**Corresponding address:**
Ozgul Akin
Cukurova University
ENT Dept. -Audiology and Speech Pathology Sect. Ankara-01330 Turkey
Phone: +90 322 338 6466; Fax: +90 322 338 6754; E-mail: oakin@cu.edu.tr

represented one after the other (Difference Limen for Frequency; DLF) and the second is the determination of modulation quantity in the level of frequency modulated tones (Frequency Modulation Difference Limen; FMDL). These two methods are important for frequency discrimination mechanisms of pure and complex tones [13]. In DLF, frequency discrimination depends on the frequency of tones, but in FMDL, it is less dependent on frequency [19, 20]. Zwicker [19] suggested that in FMDL, the excitation pattern concept is important. Frequency changes significantly affect the excitation pattern of the basilar membrane. Zwicker's excitation pattern concept revealed that stimulus changes of 1 dB or more over the excitation pattern in the basilar membrane make a difference for discriminating tones. He also explained the excitation pattern concept with place theory. Each fiber of auditory nerve acts as a sound band filter. If the sound is frequency modulated, the central frequencies create the excitation pattern in the auditory nerve. The large frequency modulation explained the modification of the discharge rate on the fiber.

A variety of studies have shown that the extensive musical practice can induce cortical reorganization [21-24]. Musicians demonstrate lower frequency and duration of discrimination thresholds due to cortical reorganization. These threshold differences may actually demonstrate one aspect of the neural substrate of musical expertise. Although musical expertise is solely dependent upon exceptional discrimination skills, skilled musical performance depends upon a number of technical and expressive talents and exceptional discrimination ability is a necessary component for proficient musical performance [22-26].

The few studies undertaken to examine discrimination ability in musicians and non-musicians have reported mixed results. Geringer [25] found that musicians who were presented with pairs of excerpts of familiar orchestral music were better able to discriminate pitch and tempo than non-musicians. Likewise, undergraduate music students performed better than non-music students on a pitch discrimination task [27]. Similar effects have been found for musically trained children [28]. Another study reported better pitch discrimination for musically trained subjects than untrained subjects, although no difference was found between groups for duration discrimination [29]. Pitt [5] reported that there is no relationship between musical education and rhythm, although pitch discrimination ability of musically trained individuals is higher than for musically untrained individuals. Rakowski [3] suggested that pitch discrimination is not affected by white noise in musically trained individuals. Elliot et al. [4] mentioned that musically untrained individuals are less successful than musically trained individuals in the detection of musical intervals. However, there are only a few studies [3, 5, 13] on the effect of musical education on frequency discrimination using FMDL and, with this in mind, the aim of this study was to determine the effect of short- term (less than 4 years) formal music education on the performance of frequency discrimination and hearing sensitivities.

The purpose of the present study was to expand our knowledge on the basic auditory abilities of musicians compared to non-musicians. Our goals were [1] to compare frequency modulated difference limen; FMDL in musicians and non-musicians [2] to compare FMDL thresholds obtained with three different sensation levels, in order to prove which sensation level makes the difference in frequency discrimination [3] to compare hearing sensitivities in musicians and non-musicians.

## Material and Methods

Thirty-two subjects took part in two groups in this experiment. In the first group, there were 16 young adults. In this group, the age range was 19-28 years (mean 23) all of whom were, or had been, professional musicians. All were still in education and studying the 4-year Music Teaching Program at the Department of Fine Arts, Gazi University Faculty of Education. They also sang and played some musical instruments. All were at 3 years of education in music. They all had normal hearing bilaterally, with pure-tone thresholds in both ears at or below the 15 dB hearing level at octave frequencies of 125-8000 Hz (ANSI, 1969).

In the second group, the age range was 19-27 years (mean 21.5). They all had normal hearing bilaterally, with pure-tone thresholds in both ears at or below the 15 dB hearing level at octave frequencies of 125-8000 Hz (ANSI, 1969) and all were studying a 4-year course at the Department of Physical Therapy at Hacettepe University Health Sciences Faculty. No one was playing a musical instrument and none had prior experience in psycho-acoustic tasks.

The audiometric tests and FMDL tests were carried out with an Interacoustics AC-40 clinical audiometer with with TDH 39 headphone and MX41/AR cushion in Industrial Acoustics Company (IAC) standard sound treated rooms to determine air conducted thresholds between 125 and 16,000 Hz. Otoscopy was followed by tympanometry on Interacoustic AZ22 middle ear analyzer.

A clinical adaptation of the frequency discrimination procedure [30] was used for measurement of FMDLs on Interacoustics AC-40 clinical audiometer. An adaptive (three-down, one-up) task converging on the probability of correct response of 0.794 [31] was used for measurement of FMDLs.

Subjects were first trained to listen for a difference between two tones with widely differing modulation (0% FM and 5% FM) until they reached a 100% criterion of consistent responses. Next, subjects listened in the experimental procedure to a sequence of two tones: 1) an unmodulated standard tone; and 2) a frequency modulated tone varying in modulation (5, 3, 2, 1, 0.8, 0.6, 0.4, 0.2, and 0%). Subjects were required to report an audible difference ("yes") between modulated and unmodulated tones by pressing a response button. Modulation was varied adaptively, i.e., decreased after three "yes" responses and increased after one "no" response. Frequency modulation difference limen (FMDL) was defined as the smallest detectable difference in frequency modulation between the modulated tone and unmodulated standard tone. Repeatability of the FMDL response was required on a successive run for test-retest reliability purposes. The intervals were separated by a 20-ms silence. Scoring made by hand scoring. Correct answer feedback was provided by lights on the response box.

FMDL test stimuli were presented in the order of 20 dB SL, 40 dB sensation level (SL) and 60 dB SL. Different sensation levels were used to determine the desired sensation level which improved the FMDL performance for musicians and non-musicians. The amount of modulation required for detection was determined as 0.2%, 0.4%, 0.6%, 0.8%, 1%, 2%, 3%, and 5% at frequencies between 125-8000 Hz.

To establish FMDLs in the following frequency order: 1000 Hz, 2000 Hz, 4000 Hz, 6000 Hz, 8000 Hz, 500 Hz, 250 Hz, and 125 Hz.

All tests were carried out in one session.

## Results

The primary question addressed in this study was whether musicians' ears show better frequency discrimination (smaller FMDLs) than nonmusicians.

In FMDL tests at 20, 40, and 60 dB SL modulation rate, differences between the first and second groups are statistically significant for the left and right ear at 125-8,000 Hz. (Figures 1-6). There were significant ($p< 0.05$) differences between musicians versus nonmusicians right ear frequency discrimination performance at 20 dB SL 125 Hz (t =2,65; p =0,0126), 250 Hz (t =3,001; p =0,0054), 500 Hz (t =2,270; p =0,0305), 1,000 Hz (t =2,153; p =0,039), 2,000 Hz (t =2,819; p =0,0085), 4,000 Hz (t =3,139; p =0,0038), 6,000 Hz (t =3,627; p =0,0011), 8,000 Hz (t =3,694; p =0,0009).

There were also significant ($p < 0.05$) differences between musicians versus nonmusicians left ear frequency discrimination performance at 20 dB SL 125 Hz (t =2,879; p =0,0073), 250 Hz (t =3,629; p =0,0010), 500 Hz (t =3,470;p =0,0016), 1,000 Hz (t =2,716; p =0,0109), 2,000 Hz (t =3,073; p =0,0045), 4,000 Hz (t =2,089; p =0,0453), 6,000 Hz (t =3,601; p =0,0011), 8,000 Hz (t =4,849; p <0,0001).

There were significant ($p< 0.05$) differences between musicians versus nonmusicians right ear frequency discrimination performance at 40 dB SL 125 Hz (t =3,847; p =0,0006), 250 Hz (t =3,662; p =0,001), 500

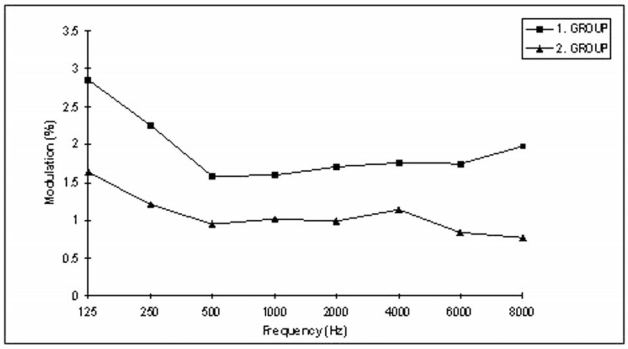


**Figure 1.** FMDL values at 20 dB SL for left ears of first and second groups.

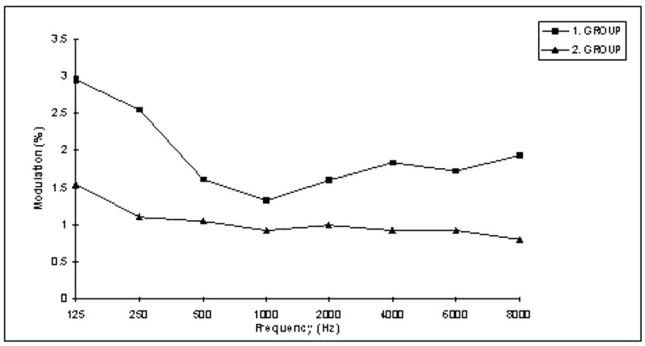


**Figure 2.** FMDL values at 20 dB SL for right ears of the first and the second groups.

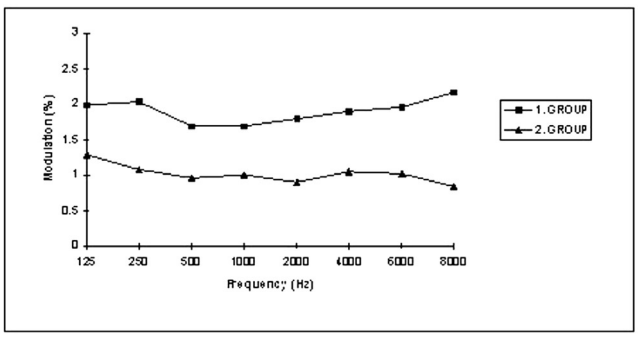


**Figure 3.** FMDL values at 40 dB SL for right ears of the first and the second groups.

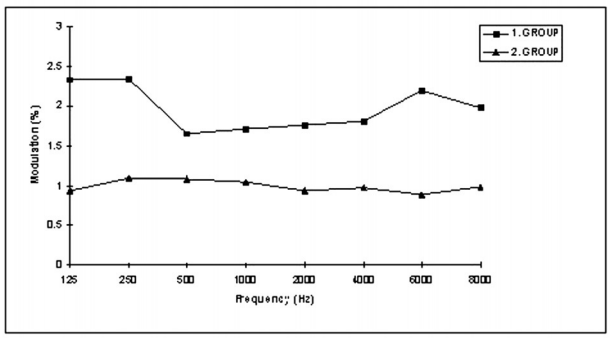


**Figure 4.** FMDL values at 40 dB SL for left ears of the first and the second groups.

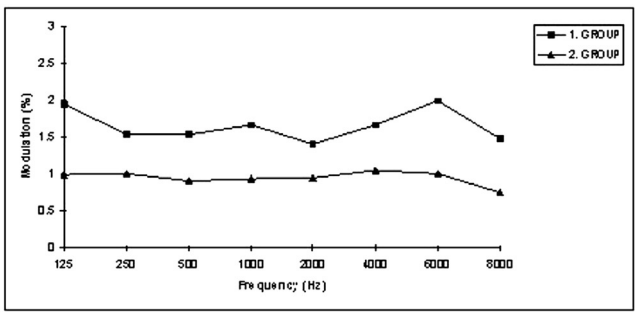


**Figure 5.** FMDL values at 60 dB SL for right ears of the first and the second groups

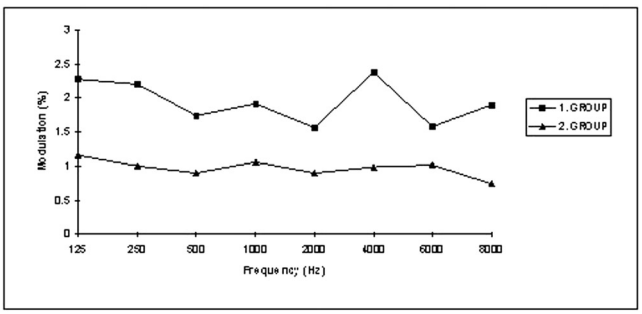


**Figure 6.** FMDL values at 60 dB SL for left ears of the first and the second groups

Hz (t =2,353; p =0,0254), 1000 Hz (t =2,919; p =0,0066), 2,000 Hz (t =2,766; p =0,0096), 4,000 Hz (t =3,354; p =0,0022), 6,000 Hz (t =3,631; p =0,001), 8,000 Hz (t =2,951; p =0,0061). There were also significant ($p < 0.05$) differences between musicians versus nonmusicians left ear frequency discrimination performance at 40 dB SL 125 Hz (t =2,186; p =0,036), 250 Hz (t =3,989; p =0,0004), 500 Hz (t =3,256; p =0,0028), 1,000 Hz (t =2,704; p =0,0112), 2,000 Hz (t =3,209; p =0,0032), 4000 Hz (t =2,922; p =0,0066), 6,000 Hz (t =2,926; p =0,0065), 8,000 Hz (t =3,738; p =0,0008).

There were significant ($p< 0.05$) differences between musicians versus nonmusicians right ear frequency discrimination performance at 60 dB SL 125 Hz (t =2,540; p =0,0165), 250 Hz (t =3,093; p =0,0043), 500 Hz (t=3,640; p =0,001), 1,000 Hz (t=3,049; p=0,0048), 2,000 Hz (t=2,848; p=0,0079), 4,000 Hz (t =3,437;p

=0,0017), 6,000 Hz (t =2,451; p =0,0203), 8,000 Hz (t =2,976; p =0,0057).

There were also significant ($p < 0.05$) differences between musicians versus nonmusicians left ear frequency discrimination performance at 60 dB SL 125 Hz (t =2,305;p =0,0283), 250 Hz (t =2,05; p =0,0492), 500 Hz (t =2,586; p=0,0148), 1,000 Hz (t=2,694; p =0,0114), 2,000 Hz (t=2,233; p =0,0332), 4,000 Hz (t =2,265; p=0,0309), 6,000 Hz (t =2,760; p=0,0098), 8,000 Hz (t =2,626; p =0,0135).

(1) In the 500-4,000 Hz frequency range, both musicians and non-musicians are more capable of differentiating modulation rates at all sensation levels.

(2) Finding shows that, at frequencies of 125 Hz, 250 Hz and 8,000 Hz, musicians are more capable of differentiating modulation rates at all SLs:

a. At frequency 125 Hz, the difference among 20 dB, 40 dB and 60 dB SL is not statistically significant (chi-square= 6.5, $p<0.05$). The difference is statistically significant between 20 dB SL and 60 dB SL ($p<0.05$).

b. At frequency 250 Hz, the difference among 20dB, 40 dB and 60 dB SL is not statistically significant (chi-square= 6.21, $p<0.05$). The difference is statistically significant between 20 dB SL and 60 dB SL and between 40 dB SL and 60 dB SL ($p<0.05$).

c. At frequency 8,000 Hz, the difference among 20dB, 40 dB and 60 dB SL is not statistically significant (chi-square= 6.03, $p<0.05$). The difference is statistically significant between 40 dB SL and 60 dB SL ($p<0.05$).

(3) A student t test was used to find out whether hearing thresholds differed significantly between musicians and non musicians. No significant results were found between groups for any tested frequencies. The both groups were found equally sensitive to pure tones at all tested frequencies (Figure 7- 8) (Table 1).

## Discussion

There are growing indications that those who study music, particularly those who start at an early age, show neurological differences when compared to those who have not had much training. Adult musicians have stronger and faster brain responses to musical tasks [32] and certain parts of their brains, related to music processing, are larger or more responsive [33-39]. All of this research strongly suggests that early musical experiences imprint themselves on the brain as do all learning experiences that have the potential for changing brain organization.

In literature, there are very few studies on the frequency discrimination ability in musicians and non-musicians. In recent studies, the FMDL test was used to study the performance of frequency change detection [19, 40]. In his study, Pitt proposes that pitch differences are more easily detected by musically educated individuals [5] while Barsz suggests that musical education is important in making decisions on whether sounds are the same or different [41]. In the present study, the second group's modulation thresholds were lower in all SLs, and pure tone thresholds at test frequencies were numerically lower than in the first group. This proves that frequency discrimination performance is developed by musical education.

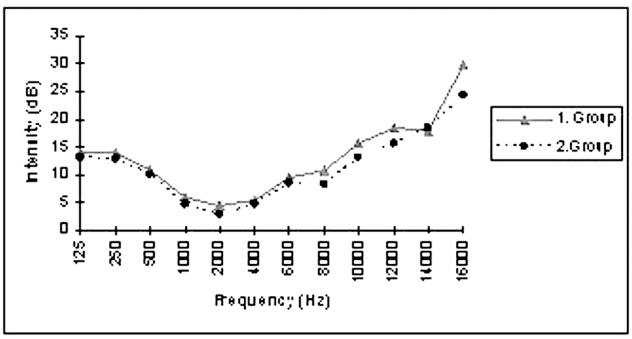


**Figure 7.** mean right pure tone hearing thresholds of first and second group

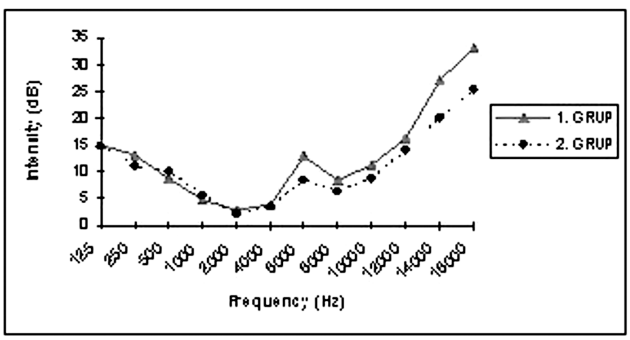


**Figure 8.** mean left ear pure tone hearing thresholds of first and second group

**Table 1.** t and p values for hearing thresholds. When the calculated P value is less than 0.05 (P<0.05), the conclusion is that the two means are significantly different.

| | 125 Hz | 250 Hz | 500 Hz | 1,000 Hz | 2,000 Hz | 4,000 Hz | 6,000 Hz | 8,000 Hz | 1,0000 Hz | 1,2000 Hz | 1,4000 Hz | 1,6000 Hz |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R | t=1,754 | t=2,95 | t=1,762 | t=1,179 | t=1,742 | t=1,179 | t=-1,762 | t=-1,23 | t=1,533 | t=0,651 | t=-1,89 | t=0,649 |
| | p=0,0897 | p=0,7697 | p=0,0849 | p=0,2479 | p=0,918 | p=0,2479 | p=0,0883 | p=0,225 | p=0,1357 | p=0,5199 | p=0,068 | p=0,521 |
| L | t=-0,110 | t=-0,87 | t=0,640 | t=0,886 | t=-0,585 | t=-0,688 | t=-2,032 | t=-1,29 | t=-1,162 | t=-0,727 | t=-1,61 | t=-1,52 |
| | p=0,913 | p=0,39 | p=0,5269 | p=0,3825 | p=0,5632 | p=0,4968 | p=0,0511 | p=0,225 | p=0,254 | p=0,472 | p=0,116 | p=0,137 |

Crummer et al. mentioned that brain activity, memory and information processing may vary depending on the level of musical education. In addition, they showed that these differences are contingent on hemispheric lateralization [40]. In this study, we suggest that the superiority of the right ear at all sensation levels for differentiating modulation rates depends on hemispheric lateralization.

Discrimination of the frequency of a sound is more important than the effect of temporal characteristics [18]. In the present study, the impact of different SLs on frequency discrimination ability are considered at three levels and it has been found that as the level increases, the modulation threshold decreases. Wier et al. suggest that the relationship between SL and DLF is linear; therefore, individuals have lower modulation thresholds at high SLs [17]. The results of the present study are similar to those of Wier et al. At 125 Hz, 250 Hz and 8,000 Hz frequencies, the differences among 20 dB, 40 dB and 60 dB SL are statistically significant ($p < 0.05$) and at 60 dB SL, frequency discrimination performance is better at 125 Hz, 250 Hz and 8,000 Hz.

He et al. showed that better modulation thresholds occur at higher SLs [42]. However, Ozimek and Sek suggested that FMDL is not dependent on the sound pressure level, but they only studied at a central frequency of 1,000 Hz, therefore they have limited results for FMDL [18].

In their study, Verschuure and van Meerteren stated that pitch variations were decreasing at 1-2 kHz, therefore high frequencies were increasing [43]. The results of the present study agree with the study of Verschuure and van Meeteren so that the differences between modulation thresholds at low and high frequencies at 60 dB SL are numerically lower for both groups [43].

In the literature, the relationships between intensity level and pitch variations are explained by place theory [44]. However, the frequency discrimination at low frequencies is explained by temporal theory and at higher frequencies, it is explained by place theory. In addition, Dye and Hafter explained that frequency perception increases with increasing level of intensity [45]. In the present study at 60 dB SL, its lower modulation thresholds at 125 Hz and 250 Hz can be explained by temporal theory and at 8,000 Hz by place theory [20, 46].

Another result of this study was to determine the frequency range for lower modulation threshold. The aim was to show the effect of frequency on frequency discrimination so that the 500-4,000 Hz frequency range was the range for lower modulation threshold. This result confirms Zwicker's model. Zwicker proposed that frequency discrimination can be explained by the excitation pattern of the stimulus while frequency changes so that excitation patterns at lower frequencies limit higher values, but at higher frequencies, the excitation pattern varies randomly. Emmerich et al. [41] indicated better performance in frequency discrimination in the 0.5-4 kHz frequency range and Heeley and Timney [47] suggested that frequency discrimination ability increases at high spatial frequencies compared with low frequencies.

Music is a way of thinking in sounds. Gardner stated that music intelligence is equal in importance to logical-mathematical intelligence, linguistic intelligence, spatial intelligence, bodily-kinesthetic intelligence, interpersonal intelligence, and intrapersonal intelligence [48]. To ensure a comprehensive learning experience, music must be included in early childhood.

Studies using these techniques can provide information regarding if and how music education influences auditory perception. We look forward to developing these methods in auditory training of hearing impairment. Music could be a useful tool with which to motivate and enliven these sessions.

## References

1. Rasch RA, Plomp R. The perception of musical tones. In: Deutsch D, editor. The psychology of music. New York: Academic Press; 1982. p. 1-21.

2. Francés R. The perception of music. NJ: Lawrence Erlbaum Associates; 1988. p. 9-38.

3. Rakowski A. Pitch discrimination and musical interval recognition in backward masking. In: Kleinke R, Hartman R, editors. Hearing. Psychological bases and psychophysics. Proceedings of the 6th International Symposium on Hearing. Bad Nauheim, Germany; 1983. p. 315-20.

4. Elliot J, Platt JR, Racine RJ. Adjustment of successive and simultaneous intervals by musically experienced subjects. Percept Psychophys 1987; 42:594-8.

5. Pitt MA. Perception of pitch and timbre by musically trained and untrained listener. J Exp Psychol Hum Percept Perform 1994; 20:976-86.

6. Kishon-Rabin L, Amir O, Vexler Y, Zaltz Y. Pitch discrimination: are professional musicians better than non-musicians? J Basic Clin Physiol Pharmacol 2001; 12 (2 Suppl):125-43.

7. Chandrasekaran B, Krishnan A, Gandour JT. Relative influence of musical and linguistic experience on early cortical processing of pitch contours. Brain Lang March 14 2008 (EPub ahead of print).

8. Kazkayasi M, Yetiser S, Ozcelik S. Effect of musical training on musical perception and hearing sensitivity: conventional and high-frequency audiometric comparison. J Otolaryngol 2006; 35:343-8.

9. Johnson DW, Sherman RE, Aldridge J, Lorraine A. Extended high frequency hearing sensitivity. A normative threshold study in musicians. Ann Otol Rhinol Laryngol 1986; 95(2 Pt 1):196-202.

10. Yucel E, Belgin E. Speech and musical perception in cochlear implant and hearing aid user adolescents. Mediterr J Otol 2006; 2: 27-35

11. Chartrand JP, Belin P. Superior voice timbre processing in musicians. Neurosci Lett 2006; 405:164-7.

12. Moore BCJ. The perception of sound. In: Wright D, editor. Scott-Brown's otolaryngology. Basic sciences. 5th ed. New York: Wiley; 1987.

13. Moore BCJ. An introduction to the psychology of hearing. 3rd edn. London: Academic Press; 1989. p. 158-94.

14. Matlin MW, Foley HJ. Sensation and perception, 3rd edn. Boston: Allyn and Bacon; 1992. p. 244-305.

15. Keidel WD, Kallert S, Korth M. The psychological basis of hearing. New York: Thieme-Straton Inc.; 1983.

16. Handel S. Listening. An introduction to the perception of auditory events. MA: MIT Press; 1993. p. 7-544.

17. Wier CC, Jesteadt W, Green DM. Frequency discrimination as a function of frequency and sensation level. J Acoust Soc Am 1977; 61:178-84.

18. Ozimek E, Sek A. AM and FM difference limens and their reference to amplitude-frequency changes of a sound in a room. Acta Acustica 1996; 82:114-22.

19. Zwicker E. Die Elementaren Grundlagen zur Bestimmung der Informationskapazitaet des Gehörs. Acustica 1956; 6:365-81.

20. Zwicker E. Masking and psychological excitation as consequences of the ear's frequency analysis. In: Plomp R, Smoorenburg GF, editors. Frequency analysis and periodicity detection in hearing. Leiden: Sijthoff; 1970.

21. Elbert T, Pantev C, Wienbruch C, Rockstroh B, Taub E. Increased cortical representation of the fingers of the left hand in string players. Science 1995; 270:305-7.

22. Pantev C, Oostenveld R, Engelien A, Ross B, Roberts LE, Manfried H. Increased auditory cortical representation in musicians. Nature 1998; 392:811-3.

23. Schlaug G, Jancke L, Huang Y, Steinmetz H. In vivo evidence of structural brain asymmetry in musicians. Science 1995; 267:699-701.

24. Schlaug G, Jancke L, Huang Y, Staiger JF, Steinmetz H. Increased corpus callosum size in musicians. Neuropsychologia 1995; 33:1047-55.

25. Geringer JM. Pitch and tempo discrimination in recorded orchestral music among musicians and non-musicians. J Res Music Educ 1984; 32:195-204.

26. Pantev C, Ross B, Fujioka T, Trainor LJ, Schulte M, Schulz M.Music and learning-induced cortical plasticity. Ann N Y Acad Sci 2003; 999:438-50.

27. Murray KR. Hemispheric asymmetry in the discrimination and identification of small frequency changes. Unpublished doctoral dissertation, University of Illinois, Urbana-Champaign, Illinois, 1978.

28. Soderquist DR, Moore MJ. Effect of training on frequency discrimination in primary school children. J Aud Res 1970; 10:185-92.

29. Houtsma AJ, Durlach NI, Horowitz DM. Comparative learning of pitch and loudness identification. J Acoust Soc Am 1987; 81:129-32.

30. Wier C.C, Jesteadt W, Green D.M Frequency discrimination as a function of frequency and sensation level. J Acous Soc America 1977; 61(1):178- 184.

31. Levitt H. Transformed up-down methods in psychoacoustics. J Acoust Soc Am 1971; 49(2 Suppl 2):467.

32. Besson M, Faïta F, Requin J. Brain waves associated with musical incongruities differ for musicians and nonmusicians. Neurosci Lett 1994; 168:101-5.

33. Elbert T, Pantev C, Wienbruch C, Rockstroh B, Taub E. Increased cortical representation of the fingers of the left hand in string players. Science 1995; 270(5234):305-7.

34. Flohr J, Persellin D, Miller D. Children's electrophysical responses to music. Paper presented at the 22nd International Society for Music Education World Conference, Amsterdam, Netherlands (ERIC Document PS025654); 1996.

35. Pantev C, Oostenveld R, Engelien A, Ross B, Roberts LE, Hoke M. Increased auditory cortical representation in musicians. Nature 1998; 392(6678):811-4.

36. Pascual-Leone A, Grafman J, Hallet M. Procedural learning and prefrontal cortex. Ann NY Acad Sci 1995; 15(769):61-70.

37. Andrade PE, Bhattacharya J. Brain tuned to music. J R Soc Med 2003; 96:284-7.

38. Petsche H, Pockberger H, Rappelsberger P. Music perception, EEG and musical training. EEG EMG Z Elektroenzephalogr Elektromyogr Verwandte Geb 1985; 16(4):183-90.

39. Williamson S, Kaufman L. Auditory evoked magnetic fields. In: Jahn A, Santos-Sacchi J, editors. Physiology of the ear. New York: Raven Press; 1988. p. 497-505.

40. Crummer GC, Walton JP, Wayman JW, Hantz EC, Frisina RD. Neural processing of musical timbre by musicians, nonmusicians and musicians processing absolute pitch. J Acoust Soc Am 1994; 95:2720-7.

41. Barsz K. Accuracy of same/different judgments of sequences of complex tones differing in tonal order under various levels of fundamental frequency range, listener training, and type of standard sequence. J Acoust Soc Am 1996; 99:1660-9.

42. He N, Dubno JR, Mills JH. Frequency and intensity discrimination measured in a maximum-likelihood procedure from young and aged normal-hearing subjects. J Acoust Soc Am 1988; 103:553-65.

43. Verschuure J, van Meeteren AA. The effect of intensity on pitch. Acustica 1975; 32:33-44.

44. Pickles JO. An introduction to the physiology of hearing. London: Academic Press; 1982. p. 1-269.

45. Dye RH Jr, Hafter ER. Just-noticeable differences of frequency for masked tones. J Acoust Soc Am 1980; 67:1746-53.

46. Moore BCJ. Frequency difference limens for short duration tones. J Acoust Soc Am 1973; 54:610-9.

47. Heeley DW, Timney B. Spatial frequency discrimination at different orientations. Vision Res 1989; 29:1221-8.

48. Gardner H. Frames of mind: The theory of multiple intelligences. New York: Basic Books; 1983. p. 5-56.