BNAM 2018
Baltic-Nordic Acoustics Meeting
15-18 April 2018
Harpa, Reykjavík, Iceland

Effects of musical training and hearing loss on pitch discrimination

Sébastien Santurette
Hearing Systems, Department of Electrical Engineering, Technical University of Denmark, Ørsteds Plads 352, DK-2800 Kgs. Lyngby, Denmark;
Department of Otolaryngology, Head and Neck Surgery, and Audiology, Rigshospitalet, Blegdamsvej 9, DK-2100 København Ø, Denmark;
ses@elektro.dtu.dk

Federica Bianchi and Torsten Dau
Hearing Systems, Department of Electrical Engineering, Technical University of Denmark, Ørsteds Plads 352, DK-2800 Kgs. Lyngby, Denmark

Our ability to perceive the pitch of complex sounds is essential for melody perception and for our enjoyment of music. It also plays an important role in speech perception to convey intonation and sometimes meaning, e.g., in tonal languages, and greatly helps segregation of competing sound sources. Humans are able to discriminate very small changes in the pitch of complex harmonic sounds, with fundamental frequency difference limens (F0DLs) that can be smaller than 1% of the fundamental frequency (F0). However, performance in such pitch discrimination tasks is known to depend on the harmonic content of the sound and whether the harmonics are resolved by the auditory frequency analysis operated by cochlear processing. F0DLs are also heavily influenced by the amount of musical training received by the listener and by the spectrotemporal auditory processing deficits that often accompany sensorineural hearing loss. This paper reviews the latest evidence for how musical training and hearing loss affect pitch discrimination performance, based on behavioral F0DL experiments with complex tones containing either resolved or unresolved harmonics, carried out in listeners with different degrees of hearing loss and musicianship. A better understanding of the interaction between these two factors is crucial to determine whether auditory training based on musical tasks or targeted towards specific auditory cues may be useful to hearing-impaired patients undergoing hearing rehabilitation.

1 Pitch and fundamental frequency discrimination

Pitch has been defined as “that attribute of auditory sensation whose variation is associated with musical melodies” [1]. It is closely linked to the presence of periodicity in sound signals and is often described as the perceptual counterpart of the frequency attribute in physical acoustics. Typically, a sound is indeed said to have a pitch if a listener can reliably match the frequency of a pure tone of arbitrary amplitude to it [2]. In addition to playing a crucial role in music perception, pitch is an essential auditory cue to convey prosodic and semantic information in speech and contributes greatly to sound source segregation and auditory grouping [1].

In our environment, most pitch evoking sounds, such as speech, musical sounds, and animal vocalizations, have a strongly harmonic frequency content, such that the most prominent frequency components (Fn) in their spectrum all correspond to integer multiple frequencies of a common fundamental frequency (F0): Fn = N × F0, where N is the harmonic number. This means that harmonics are typically equally spaced on a linear frequency scale, with a spacing equal to F0 (see Figure 1 for the example of a note produced by a violin).

The frequency selectivity of the human auditory system, first arising in the inner ear due to the mechanical properties of the basilar membrane in the cochlea, is known to worsen on a linear scale as frequency increases. This property can for instance be modelled as a bank of bandpass filters with increasing bandwidths as a function of linear frequency [3] and has important consequences for the representation of pitch-evoking harmonic sounds. In the normal auditory system, the lower harmonics are indeed sufficiently separated by this cochlear filtering process such that information about their individual frequencies is still retrievable after the cochlear stage of auditory processing. Such harmonics are thus termed "resolved" and typically correspond to N ≤ 6. In contrast, the higher harmonics, for about N ≥ 12, are termed "unresolved", as they interact with neighboring harmonics within broader auditory filters, such that information about their individual frequencies is lost after the cochlear stage. See [4] for a more detailed presentation of the resolvability concept. Resolved harmonics produce a salient pitch and typically dominate the overall pitch percept for complex sounds. However, unresolved harmonics, when presented alone, can still produce a less salient pitch corresponding to the (missing) F0.

The mechanisms by which the pitch of complex sounds is retrieved are still heavily debated [5]. However, the information that can be used for pitch retrieval by the auditory system is known to depend on the resolvability of the harmonics present in the incoming sound. For resolved harmonics, the *place* of maximal excitation on the basilar membrane, later reflected in the firing rate of auditory nerve cells, may provide a pitch cue. In addition, the precise *timing* of auditory neural spikes, which at low frequencies phase-lock to the vibration waveform of the basilar membrane, provides a way of coding the periodicity of individual harmonics as well as the overall stimulus periodicity. For unresolved harmonics, while place cues and timing cues related to individual harmonics are unavailable after the cochlear stage, the overall periodicity can still be retrieved via timing cues due to the strong *temporal envelope* fluctuations created by interacting harmonics. See [5] for an overview of proposed pitch perception models based on such potential pitch cues.

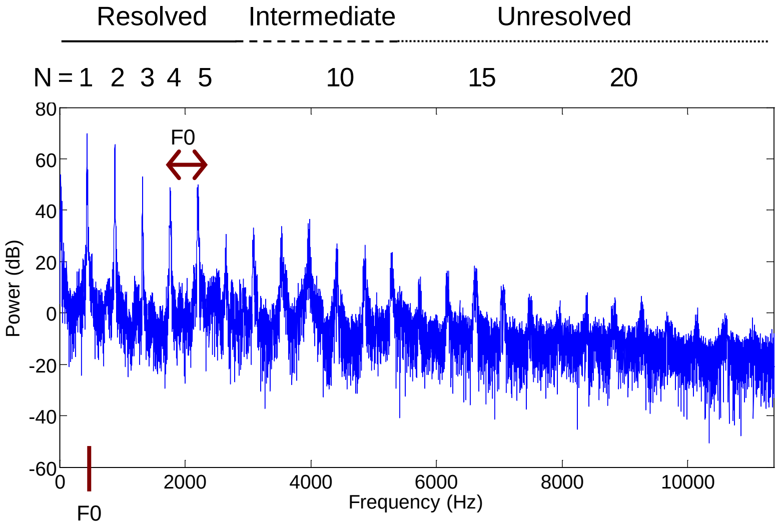


Figure 1: Frequency spectrum of a violin note corresponding to A4 (F0 ≈ 440 Hz). F0: fundamental frequency. N: harmonic number. In the normal auditory system, the lower harmonics (N ≤ 6) are resolved by the peripheral auditory system, while the upper harmonics (N ≥ 12) are unresolved, with an intermediate transition region in between.

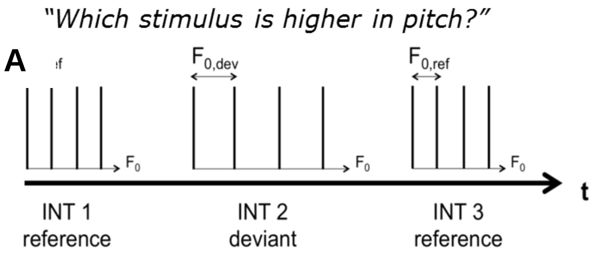
The ability of human listeners to discriminate pitch can be estimated by measuring the smallest detectable change in F0 for a complex tone containing a given set of harmonics. Such F0 difference limens (F0DLs) have been found to be much lower when resolved harmonics are present in the stimulus than when it does only contain unresolved harmonics [6], although such difference in performance might depend more on harmonic number rather than on resolvability *per se* [7]. In the presence of resolved harmonics, humans are extremely accurate in such pitch discrimination tasks, with F0DLs typically under 1% of F0 [6]. As a comparison, the smallest musical interval in Western music, the semitone, corresponds to about 6% of F0. If such pitch discrimination performance is typical of an average normal-hearing (NH) listener, F0DLs are however known to be greatly affected by the amount of musical experience and by the hearing status of the listener. In the following sections, this paper reviews some of the evidence for such effects and the suggested mechanisms that underlie them.

2 Effects of musical training on pitch discrimination

Several studies have reported better pitch discrimination performance in listeners with musical training compared to non-musicians, for both pure tones [8, 9, 10] and complex tones [10, 11]. This "musician's advantage" may be ascribed to several changes that musical training has been suggested to yield along the auditory system. First, functional and structural differences in the brain have been observed for musicians vs. non-musicians, such as increased neural activity in response to musical sounds [12], increased grey matter volume in motor, auditory, and spatial cortical regions [13] and larger auditory cortex volume [14]. Second, changes induced by musical training may occur at a sub-cortical level, with enhanced temporal representations in the brainstem of musicians [15]. Third, it may be that frequency selectivity, potentially already at a peripheral level, is higher in musicians compared to non-musicians [16].

In order to clarify which of these potential factors mostly contribute to the enhanced pitch discrimination abilities of musicians, Bianchi et al. performed a series of behavioral F0DL experiments in groups of musically-trained and non-musically-trained listeners [11, 17], supplemented by objective measures of processing effort, as reflected by pupil dilation [11], and cortical activity, as reflected by functional magnetic resonance imaging (fMRI) [17].

F0DLs were measured using a 3-alternative forced-choice paradigm in which the listeners were presented with three stimulus intervals, two of them containing a reference F0 (F0,ref) and the third, randomly chosen, interval containing a slightly higher, deviant F0 (F0,dev). The task of the listeners was to indicate the interval with the highest pitch (Figure 2A). An adaptive procedure was used to track the 75% point on the psychometric function, defined as the F0DL. By filtering the complex tones in a fixed high-frequency region, the resolvability of the stimuli could be varied by measuring F0DLs for different F0,ref values (Figure 2B). For low F0,ref values, the complex tones were unresolved and high pitch discrimination thresholds were expected, while for high F0,ref values, the complex tones were resolved and better performance (i.e., lower thresholds) were expected (Figure 2C). A control condition with complex tones filtered in a low-frequency region, and thus always resolved independently of F0,ref, was also included. Performance was compared between trained musicians and listeners without musical training. The transition point at which F0DLs decreased due to the presence of resolved components, F0,tr, was also estimated for the two listener groups.



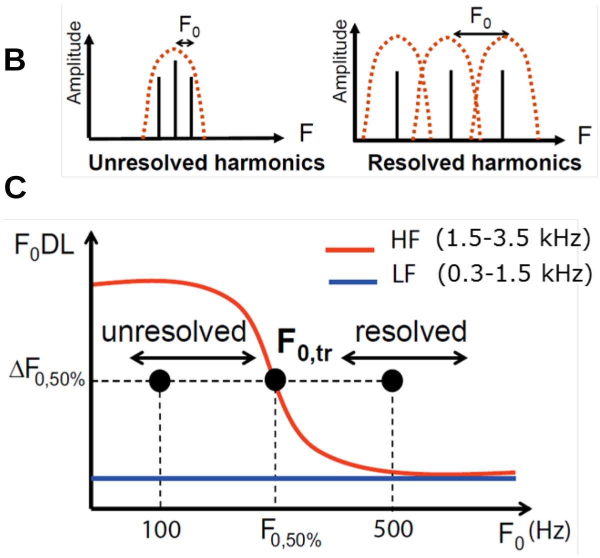


Figure 2: (A) Schematic illustration of a 3-alternative forced-choice F0DL trial. (B) Sketch of unresolved (left) and resolved (right) harmonics, the dotted line representing auditory filters. (C) Schematic illustration of F0DLs as a function of F0 for complex tones filtered in a high (HF, red curve) and low (LF, blue curve) frequency region. F0,tr denotes the transition point between good and poor performance.

The behavioral results, summarized in Figure 3A, showed that musicians had significantly lower F0DLs for both resolved and unresolved complex tones (conditions R[11] and U[11] in Figure 3A), consistent with findings from another study [18]. As pitch coding for unresolved harmonics is believed to rely exclusively on temporal envelope cues, better performance for the unresolved conditions is most probably not related to a potential enhancement of frequency selectivity in musicians. Moreover, there was no significant difference between the estimated F0,tr values in the two listener groups (mean and standard deviations: 174 ± 45 Hz in musicians and 192 ± 30 Hz in non-musicians, see [11]). Therefore, the results did not support higher frequency selectivity in musically-trained listeners.

The question then arises of whether musicians do show enhanced F0 representations at higher stages of the auditory system. If so, they may be advantaged in terms of the amount of cognitive effort required to process the stimuli during pitch discrimination tasks. In [11], processing effort was assessed using pupillometry. Pupil size was tracked for the two listener groups during pitch discrimination measurements in which the task difficulty was varied by setting the difference between F0,ref and F0,dev to individual performance levels of either 90% correct (easy), 75% correct (medium difficulty), or 60% correct (difficult). Figure 3B shows that, as the listeners are presented with the three intervals and provide their response, their pupil dilates more on average and its size takes longer to return to baseline for the difficult (black curve) than for the medium (red curve) and easy (blue curve) conditions. The mean group results for the resolved condition, summarized in Figure 3C, show that this effect was stronger in the musicians (left panel) than in the non-musicians (right panel). Moreover, the musicians showed significantly smaller pupil dilations across conditions, despite the fact that task difficulty was adjusted based on individual F0DL performance. Therefore, these findings suggest that musicians need to allocate fewer cognitive resources than non-musicians to reach the same performance level (and obtain lower thresholds) in pitch discrimination tasks.

Could this lower processing effort in musicians then stem from enhanced F0 representations at subcortical or cortical levels? In a subsequent study [17], musicians and non-musicians were asked to perform a behavioral pitch discrimination task inside an MR scanner while fMRI responses were obtained in an event-related acquisition paradigm. The complex tones were similar to [11] and task difficulty was adjusted on an individual basis. The results (see [17] and Figure 3D) showed that musicians exhibited stronger responses in a number of both cortical (e.g., the right posterior superior temporal gyrus) and subcortical (e.g., the inferior colliculus) areas. Moreover, behavioral F0DLs for resolved conditions were significantly correlated with responses in the right auditory cortex in musicians, and a significant correlation between F0DLs and brainstem responses from the inferior colliculus was found when pooling listeners from both groups. In conclusion, the results provide evidence for training-dependent plasticity at both subcortical and cortical levels in musicians, with a link between stronger responses in the right auditory cortex and increased behavioral pitch discrimination performance.

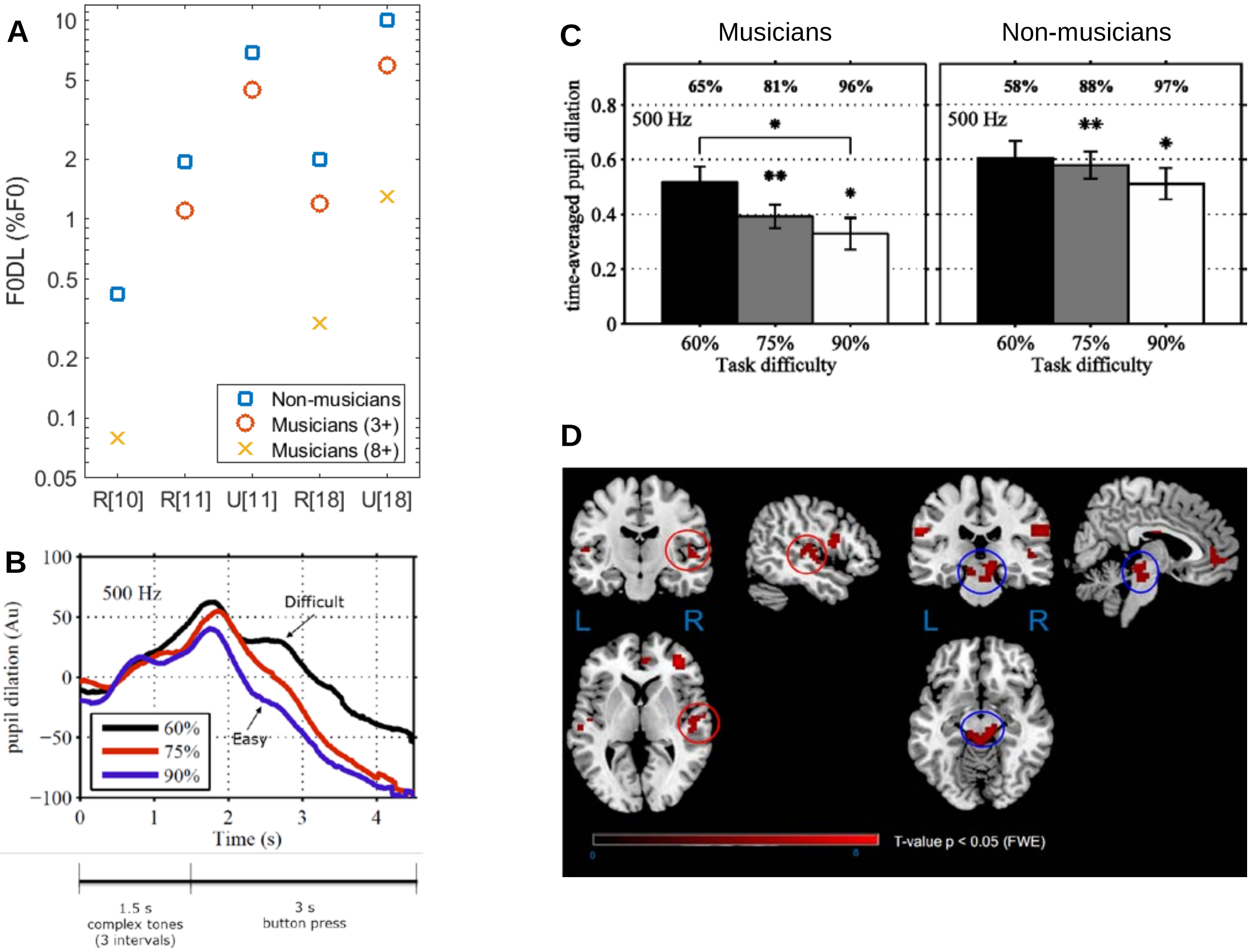


Figure 3: (A) F0DLs expressed as %F0 for non-musicians (squares), musicians with at least 3 years of formal training (circles), and musicians with at least 8 years of formal training (crosses). The mean results from three studies [10, 11, 18] are replotted for resolved (R) and unresolved (U) conditions. Note that the lower thresholds obtained in [10] may be due to the use of low-numbered harmonics only, the absence of background noise, or longer training of the listeners. (B) Pupil dilation examples over the course of a resolved pitch discrimination trial for three task difficulty levels. (C) Mean pupil dilations for musicians (left panel) and non-musicians (right panel) as a function of task difficulty for resolved conditions. Percentages indicate actual behavioral performance. Based on an early analysis of data from [11]. (D) Differential fMRI activation map to the contrast musicians > non-musicians. Activation in right auditory cortex (red circle), middle frontal gyrus, and inferior colliculus (blue circle). Based on an early analysis of data from [11].

3 Effects of sensorineural hearing loss on pitch discrimination

In addition to decreased hearing sensitivity, listeners with sensorineural hearing loss (SNHL) typically exhibit decreased frequency selectivity, reflected by broader auditory filters. This may affect both place and timing cues relevant for pitch extraction and lead to a loss of resolvability of lower harmonics that are typically resolved in NH listeners. Therefore, hearing-impaired (HI) listeners may show elevated F0DLs for stimuli containing resolved harmonics [19, 20] and rely more on unresolved harmonics than NH listeners. Moreover, there is evidence from animal electrophysiology that SNHL may enhance the amplitude and accuracy of temporal envelope coding in the auditory nerve [21]. As the pitch elicited by unresolved harmonics is believed to rely on temporal envelope cues, this may explain why F0DLs in unresolved conditions are not necessarily elevated in listeners with SNHL [19]. Two of the possible reasons for increased envelope amplitude in the HI auditory nerve may be a) reduced frequency selectivity, leading to more harmonics interacting within each auditory filter, and b) reduced cochlear compression.

In order to test whether such envelope enhancement could be observed in human listeners and affected their pitch perception for unresolved harmonics, Bianchi et al. compared F0DLs for unresolved complex tones with harmonics added in sine phase (SP), yielding a peaky envelope, and complex tones with harmonics added in random phase (RP), yielding flatter envelopes on average (Figure 4A), for two groups of NH and HI listeners [22]. The results indicated that the ratio between F0DLs in the RP and the SP conditions, assumed to reflect the envelope processing enhancement, was elevated in almost all HI listeners compared to NH listeners (Figure 4B), and that this was mainly due to elevated F0DLs for HI listeners in the RP condition [22]. Moreover, individual behavioral estimates of cochlear compression in the same listeners were significantly correlated with F0DL ratios, while estimates of frequency selectivity were not. Together with predictions based on a simplified model of the auditory periphery [22], these results suggest that loss of compression may be the main factor affecting temporal envelope representations in SNHL, with consequences for pitch discrimination of unresolved complex tones.

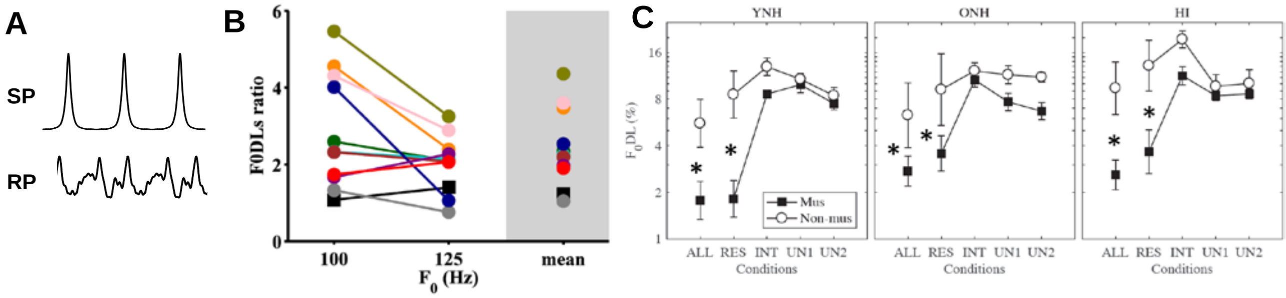


Figure 4: (A) Schematic illustration of example temporal envelope waveforms for harmonic components added in sine phase (SP, top) and random phase (RP, bottom). (B) Ratio between F0DLs for RP and SP complex tones with unresolved harmonics for NH listeners (mean value, black squares) and HI listeners (individual values, colored circles). Data from [22]. (C) Mean F0DLs for musicians (filled symbols) and non-musicians (open symbols) for the YNH (left panel), ONH (middle panel), and HI (right panel) listener groups. ALL and RES conditions contained resolved harmonics, INT intermediate harmonics, UN1 and UN2 unresolved harmonics only. Data from [23].

If musical training leads to improved pitch discrimination for both resolved and unresolved complex tones in NH listeners and SNHL is mainly detrimental for pitch discrimination in the presence of resolved harmonics, how do these two factors then interact? This issue was addressed in [23] by measuring F0DLs in younger NH (YHN), older NH (OHN), and older HI listeners, each of the three groups containing listeners with and without musical training. The results showed that musical training benefited listeners from all groups for pitch discrimination of complex tones whenever resolved harmonics were present (Figure 4C, ALL and RES conditions). Interestingly, the HI musicians obtained better average pitch discrimination performance than the YNH non-musicians in the conditions with resolved harmonics, suggesting that musical training can to some extent counteract the degradation of relevant pitch cues for resolved harmonics in SNHL. This benefit of musical training was, however, smaller in HI listeners with more severe SNHL.

Finally, a behavioral measure of temporal-fine-structure (TFS) processing performed in the same listeners was found to correlate significantly with F0DLs in conditions with resolved and intermediate harmonics [23, Fig. 3], suggesting that access to TFS cues positively affects pitch discrimination performance in these conditions. In addition, musically-trained listeners performed significantly better than non-musicians in the TFS task [23, Fig. 2], consistent with the fact that they may show increased neural synchrony to TFS, potentially leading to enhanced temporal pitch cues. In conclusion, the observed interaction between musicianship and hearing loss suggests that music-training paradigms may be promising tools to help restore auditory cues relevant for pitch perception in listeners with mild to moderate SNHL.

References

[1] Plack, C. J., & Oxenham, A. J. (2005). Overview: The present and future of pitch. In Pitch (pp. 1-6). Springer, New York, NY.

[2] Hartmann, W. M. (2004). Signals, sound, and sensation. Springer Science & Business Media.

[3] Glasberg, B. R., & Moore, B. C. (1990). Derivation of auditory filter shapes from notched-noise data. Hear. Res., 47, 103-138.

[4] Plack, C. J., & Oxenham, A. J. (2005). The psychophysics of pitch. In Pitch (pp. 7-55). Springer, New York, NY.

[5] De Cheveigne, A. (2005). Pitch perception models. In Pitch (pp. 169-233). Springer, New York, NY.

[6] Houtsma, A. J., & Smurzynski, J. (1990). Pitch identification and discrimination for complex tones with many harmonics. J. Acoust. Soc. Am., 87, 304-310.

[7] Bernstein, J. G., & Oxenham, A. J. (2003). Pitch discrimination of diotic and dichotic tone complexes: Harmonic resolvability or harmonic number? J. Acoust. Soc. Am., 113, 3323-3334.

[8] Spiegel, M. F., & Watson, C. S. (1984). Performance on frequency-discrimination tasks by musicians and nonmusicians. J. Acoust. Soc. Am., 76, 1690-1695.

[9] Kishon-Rabin, L., Amir, O., Vexler, Y., & Zaltz, Y. (2001). Pitch discrimination: Are professional musicians better than non-musicians? J. Basic Clin. Physiol. Pharmacol., 12, 125-144.

[10] Micheyl, C., Delhommeau, K., Perrot, X., & Oxenham, A. J. (2006). Influence of musical and psychoacoustical training on pitch discrimination. Hear. Res., 219, 36-47.

[11] Bianchi, F., Santurette, S., Wendt, D., & Dau, T. (2016). Pitch discrimination in musicians and non-musicians: Effects of harmonic resolvability and processing effort. J. Assoc. Res. Otolaryngol., 17, 69-79.

[12] Pantev, C., Oostenveld, R., Engelien, A., Ross, B., Roberts, L. E., & Hoke, M. (1998). Increased auditory cortical representation in musicians. Nature, 392, 811.

[13] Gaser, C., & Schlaug, G. (2003). Brain structures differ between musicians and non-musicians. J. Neurosci., 23, 9240-9245.

[14] Schneider, P., Scherg, M., Dosch, H. G., Specht, H. J., Gutschalk, A., & Rupp, A. (2002). Morphology of Heschl's gyrus reflects enhanced activation in the auditory cortex of musicians. Nature Neurosci., 5, 688.

[15] Parbery-Clark, A., Skoe, E., & Kraus, N. (2009). Musical experience limits the degradative effects of background noise on the neural processing of sound. J. Neurosci., 29, 14100-14107.

[16] Bidelman, G. M., Schug, J. M., Jennings, S. G., & Bhagat, S. P. (2014). Psychophysical auditory filter estimates reveal sharper cochlear tuning in musicians. J. Acoust. Soc. Am., 136, EL33-EL39.

[17] Bianchi, F., Hjortkjær, J., Santurette, S., Zatorre, R. J., Siebner, H. R., & Dau, T. (2017). Subcortical and cortical correlates of pitch discrimination: Evidence for two levels of neuroplasticity in musicians. NeuroImage, 163, 398-412.

[18] Santurette, S., Le Gal de Kérangal, M., & Joshi, S. N. (2015). Effects of harmonic roving on pitch discrimination. J. Acoust. Soc. Am., 137, 2226.

[19] Moore, B. C., & Peters, R. W. (1992). Pitch discrimination and phase sensitivity in young and elderly subjects and its relationship to frequency selectivity. J. Acoust. Soc. Am., 91, 2881-2893.

[20] Bernstein, J. G., & Oxenham, A. J. (2006). The relationship between frequency selectivity and pitch discrimination: Sensorineural hearing loss. J. Acoust. Soc. Am., 120, 3929-3945.

[21] Henry, K. S., Kale, S., & Heinz, M. G. (2014). Noise-induced hearing loss increases the temporal precision of complex envelope coding by auditory-nerve fibers. Frontiers Syst. Neurosci., 8, 20.

[22] Bianchi, F., Fereczkowski, M., Zaar, J., Santurette, S., & Dau, T. (2016). Complex-tone pitch discrimination in listeners with sensorineural hearing loss. Trends Hear., 20, 2331216516655793.

[23] Bianchi, F., Dau, T., & Santurette, S. (2017). Effect of musical training on pitch discrimination performance in older normal-hearing and hearing-impaired listeners. Proc. ISAAR, 6, 175-182.