Effect of musical training on fundamental frequency discrimination for older normal-hearing and hearing-impaired listeners

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Hearing-impaired (HI) listeners, as well as elderly listeners, typically have a reduced ability to discriminate the fundamental frequency (F_0) of complex tones compared to young normal-hearing (NH) listeners. Several studies have shown that musical training, on the other hand, leads to improved F_0-discrimination performance for NH listeners. It is unclear whether a comparable effect of musical training occurs for listeners whose sensory encoding of F_0 is degraded. To address this question, F_0 discrimination was investigated for three groups of listeners (14 young NH, 9 older NH and 10 HI listeners), each including musicians and non-musicians, using complex tones that differed in harmonic content. Musical training significantly improved F_0 discrimination for all groups of listeners, especially for complex tones containing low-numbered harmonics. In a second experiment, the sensitivity to temporal fine structure cues (TFS) was estimated in the same listeners. Although TFS cues were degraded for the two older groups of listeners, musicians showed better performance than non-musicians. Additionally, a significant correlation was obtained between F_0-discrimination performance and sensitivity to TFS cues for complex tones with low and intermediate harmonic numbers. These findings suggest that musical training may enhance both sensory encoding of TFS cues and F_0 discrimination in young and older listeners with or without hearing loss.

INTRODUCTION

The effects of musical training on fundamental frequency (F_0) discrimination have been largely investigated for young normal-hearing (NH) listeners. Behavioral studies have shown that young NH musicians perform two to six times better than non-musicians in complex-tone F_0 discrimination (Spiegel and Watson, 1984; Micheyl *et al.*, 2006; Bianchi *et al.*, 2016). However, little is known about the effects of musical training for older and hearing-impaired (HI) listeners. The aim of this study was to assess whether older and HI listeners show a benefit of musical training and to clarify the extent to which the degradation of peripheral cues is a limiting factor.

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The ability to discriminate F_0 changes is assumed to be partly limited by the frequency resolution of the peripheral auditory system. The harmonic overtones of a complex tone are considered to be resolved when they are processed within distinct auditory filters (up to the 8th harmonic for NH listeners; Plomp (1964)), and unresolved when neighbouring harmonics interact within the same filter (above the 13th harmonic). It has been shown that HI listeners with sensorineural hearing loss (SNHL) have a reduced ability to discriminate the F_0 of complex tones with resolved harmonics relative to young NH listeners (Moore and Peters, 1992; Bernstein and Oxenham, 2006). This perceptual deficit may be ascribed to a variety of factors, such as reduced frequency selectivity (Bernstein and Oxenham, 2006), degraded temporal fine structure processing (TFS; Hopkins and Moore, 2007) and decreased neural synchrony. Older listeners also show reduced F_0 discrimination (Moore and Peters, 1992), possibly due to the degradation of TFS cues, despite normal audiometric thresholds and filter bandwidths (Hopkins and Moore, 2011).

In this study, two experiments were performed using three groups of listeners, young NH (YNH), older near-NH (ONH) and older HI, each including musicians and non-musicians. In the first experiment, F_0-discrimination performance was investigated using complex tones that differed in harmonic content to clarify how the effect of musical training varies when frequency selectivity and TFS sensitivity are degraded. In the second experiment, the ability to use TFS cues was assessed for the three groups and compared with the outcomes of the first experiment.

METHOD

Listeners

Fourteen YNH listeners (7 musicians, 7 non-musicians; mean age 25 $\pm$ 4 years), nine ONH listeners (3 musicians, 6 non-musicians; mean age 62 $\pm$ 5 years) and ten HI listeners (5 musicians, 5 non-musicians; mean age 68 $\pm$ 6 years) participated in this study. All YNH listeners had hearing thresholds lower or equal to 20 dB hearing level (HL) between 125 Hz and 8 kHz. The ONH listeners had hearing thresholds lower than or equal to 25 dB HL up to 4 kHz. The HI listeners had hearing thresholds up to 70 dB HL up to 4 kHz. Musicians had at least eight years of formal music education and non-musicians less than 3 years. One non-musician underwent musical training for 6 years, but stopped 40 years before his participation in this study.

Experiment I: F_0 discrimination

A three-alternative forced choice (3-AFC) paradigm was used in combination with a weighted up-down method to estimate 75% correct performance. In each trial, two intervals contained a reference complex tone with a fixed F_0 (125 Hz) and one interval contained the target complex tone with a higher F_0. The task was to select the interval containing the tone with the highest pitch. The difference in F_0 between the reference and the target, ΔF_0, was initially set to 20% and was decreased after each correct response and increased after each incorrect response. The threshold for each condition was measured four times. The first repetition was considered as training and the last three were used to calculate the final F_0-discrimination threshold (F_0DL).

Five conditions were tested: a resolved condition (RES, harmonics: 3-9), an intermediate condition (INT, harmonics: 10-16), two unresolved conditions (UN1, harmonics: 17-23; UN2, harmonics: 17-36) and a broadband condition (ALL, harmonics: 3-36). To avoid spectral edges as a discrimination cue, the lowest harmonic number was roved within each trial, such that the three complex tones had lowest harmonic numbers of $N-1$, N and N+1 in a random order, where N was the lowest nominal harmonic number in each condition (Bernstein and Oxenham, 2003).

All signals were 300-ms complex tones embedded in broadband threshold equalizing noise (TEN). The complex tones were created by summing harmonic components either in sine, Schroeder positive or Schroeder negative phase (Schr + or -) to vary the envelope peakiness. For the NH listeners, the TEN level was set to 55 dB SPL per equivalent rectangular bandwidth (ERB_N). For the HI listeners, the level of the TEN per ERB_N was set to the maximum hearing threshold up to 4 kHz. Each harmonic of each complex tone was set at 12.5 dB sensation level (SL) re the threshold in the TEN.

Experiment II: IPD detection

To obtain an estimate of interaural phase sensitivity, the highest frequency at which an interaural phase difference (IPD) of 180°could be detected was measured using a 2-AFC paradigm with a one-up two-down tracking rule (71% correct performance). For each trial, the reference interval contained four diotic pure tones ("AAAA", IPD = 0°), each 400 ms in duration with a 100-ms inter-stimulus interval.The target interval contained two diotic and two dichotic tones (IPD = 180°), presented in a interleaved manner ("ABAB"). The interval between reference and target was of 333 ms. The task was to select the interval containing the tones that were perceived as shifting location inside the head. The starting frequency was 500 Hz. The tones were presented at 35 dB SL. The experiment was carried out three times, and the final threshold was calculated as the mean of three repetitions. Prior to carrying out the IPD experiment, the listeners had a short familiarization session (2 minutes) with a similar task, where an interaural level difference was introduced in the dichotic conditions instead of an IPD.

RESULTS

Experiment I: F_0 discrimination

The mean F_0DLs for the three groups of listeners are presented in Fig. 1. Performance was most accurate (i.e., lowest thresholds) for the ALL and RES conditions and worsened for the INT and UN conditions. Performance was worse for the ONH and HI listeners for the ALL, RES and INT conditions than for the YNH listeners. However, the effect of musical training was similar across the three groups, with significantly lower thresholds for musicians in the ALL and RES conditions. An analysis of variance (ANOVA) with factors condition, musicianship, group, and phase gave significant effects of condition [$F(4,457) = 54.8$; $p < 0.001$), musicianship [$F(1,457) = 127.2$; $p < 0.0001$], and group [$F(2,457) = 12.4$; $p < 0.001$], a significant interaction between musicianship and condition [$F(4,457) = 20.4$; $p < 0.001$], and a marginally significant interaction between group and condition [$F(8,457) = 1.96$; $p = 0.050$]. Phase was not significant, nor the interaction between musicianship and group.

The dashed line in Fig. 1 shows the thresholds (66.7% correct) predicted if performance had solely been based on spectral edge cues. Although 66.7% is lower than the tracked 75% correct performance, it is possible that thresholds significantly above the dashed line were based on spectral edge cues, rather than F_0s cues (Bernstein and Oxenham, 2003). Since most thresholds in the UN conditions were significantly above the dashed line, it cannot be excluded that for this condition the listeners used spectral edges as a cue, rather than F_0 cues.

Experiment II: IPD detection

Figure 2 depicts the highest frequency (f_{max}) at which an IPD was detected for each listener group. YNH musicians were sensitive to the IPD shift, on average, up to 1281 Hz, while YNH non-musicians were sensitive up to 1116 Hz. Sensitivity to IPD decreased for the ONH listeners (musicians: 1022 Hz; non-musicians: 761 Hz), and for the HI listeners (musicians: 993 Hz; non-musicians: 820 Hz). An ANOVA with factors group and musicianship showed a significant effect of both factors [group: $F(2,26) = 8.09$, $p = 0.002$; musicianship: $F(1,26) = 6.87$, $p = 0.014$]. The interaction was not significant. Although there was an overall trend for musicians to be sensitive to IPD up to higher frequencies, posthoc *t*-tests revealed that the effect of musicianship was not significant within each group. Additionally, the group difference was mostly driven by age (the thresholds for the ONH and HI groups were not significantly different).

Spearman correlations were calculated between the IPD f_{max} thresholds and the F_0-discrimination performance (Experiment I). A significant correlation was found for the ALL condition ($r = -0.48$; $p = 0.007$), RES condition ($r = -0.48$; $p = 0.006$), and INT condition ($r = -0.36$; $p = 0.043$) but not for the UN conditions (Fig. 3). This finding suggests that TFS cues may play a role for F_0 discrimination of complex tones containing low and intermediate numbered harmonics (Moore and Moore, 2003). No significant correlations were obtained for the musicians alone ($N = 15$), suggesting that the degradation of TFS cues with age did not affect the musicians' F_0-discrimination performance.

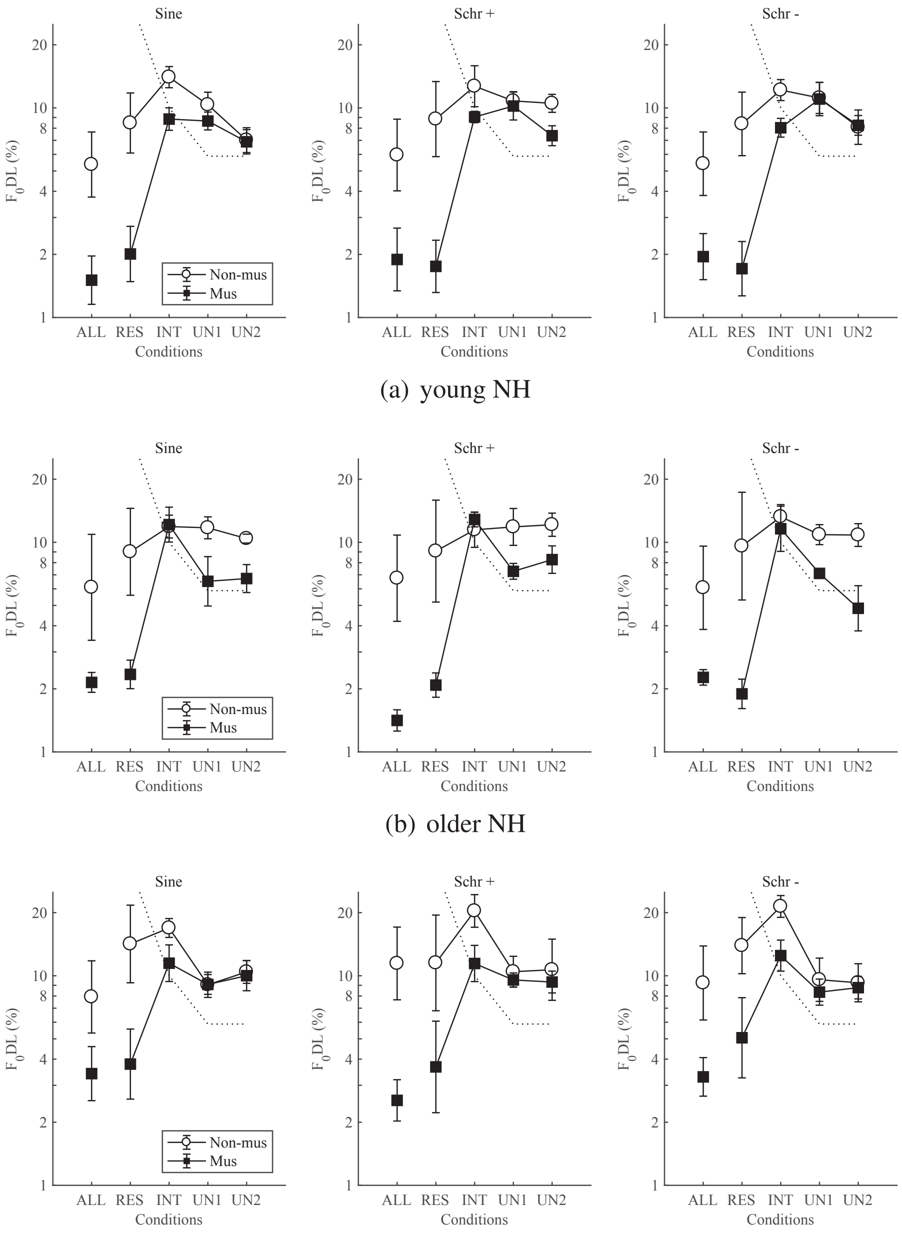

Fig. 1: Mean F_0DLs and standard errors for the three groups of listeners (N = 33): a) young NH listeners; b) older NH listeners; c) older HI listeners. Musicians are depicted with filled squares and non-musicians with open circles. Left panels: sine phase condition; Middle panels: Schroeder positive; Right panels: Schroeder negative. The dashed line depicts the predicted thresholds (66.7% correct) if the listener used only spectral edge cues.

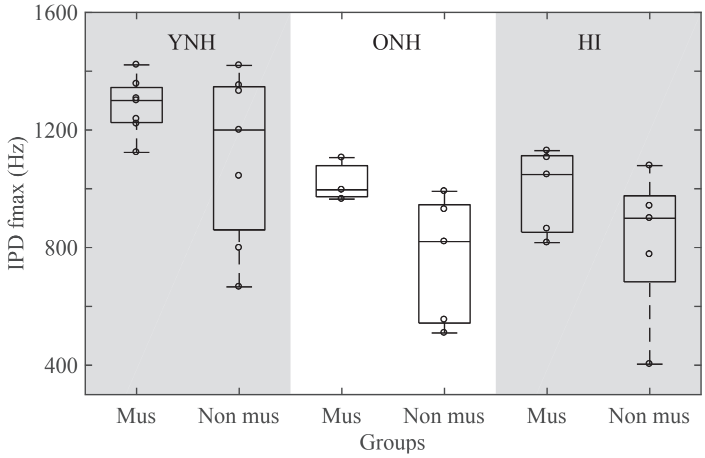

Fig. 2: Highest frequency at which an IPD was detected. The median for each group of listeners is depicted together with the 25th and 75th percentiles. The individual results are depicted by the open circles (N = 32 listeners; one ONH listener non-musician could not perform the task).

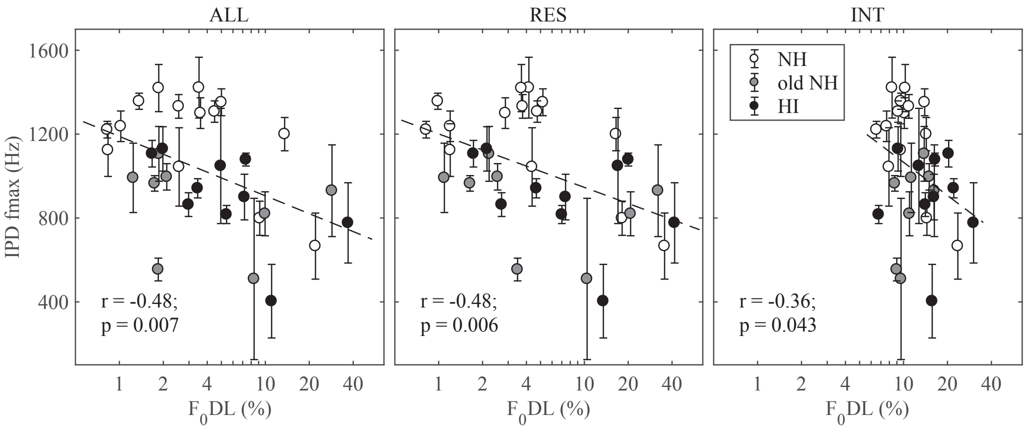

Fig. 3: Scatter plot and Spearman correlations between the IPD f_{max} thresholds and the F_0DLs averaged across phase conditions (N = 32 listeners), for the ALL (left panel), RES (middle panel), and INT (right panel) conditions.

DISCUSSION

The aim of this study was to clarify whether listeners with degraded processing of F_0 cues would show a benefit of musical training for F_0 discrimination, comparable to that observed for YNH listeners. Experiment I showed a similar benefit of musicians for the three groups of listeners (confirmed by the absence of a significant interaction of group and musicianship), with the largest benefit observed in the ALL and RES conditions. The fact that the benefit of musicians was larger in these two conditions may be ascribed either to a training-dependent effect that may be more salient for complex tones containing lower-numbered harmonics (Bianchi *et al.*, 2017) or to the random changes in the lowest harmonic number which may be more distracting for non-musicians. In favor of this last hypothesis, the F_0DLs were significantly lower (better) for the ALL than for the RES condition for non-musicians (posthoc *t*-test, $p < 0.001$), but not for musicians. This may be due either to the contribution of high-numbered harmonics in the ALL condition for non-musicians or to a reduced distraction in the ALL condition from the spectral upper-edge pitch.

The F_0DLs obtained in this study for YNH listeners in the RES condition were, on average, 1.8% for musicians and 8.5% for non-musicians. These discrimination thresholds are much higher than the F_0DLs obtained in previous studies for resolved complex tones presented at similar sensation levels as in the current study (Oxenham *et al.*, 2009; Bianchi *et al.*, 2016). This difference may be ascribed to the distracting effect of the randomization of the lowest harmonic number. Since the lowest harmonic number could differ by $\pm$ 1 across intervals, spectral edge pitch was a strong distracting cue especially for the RES condition. In this condition, spectral edge cues helped in the discrimination task only when the lowest harmonic number of the target was higher than both references (i.e., in one out of three cases, hence at chance level). In the remaining cases, the spectral edge cue was a disrupting cue in the F_0-discrimination task, leading to higher thresholds.

Although one additional aspect of this study was to investigate the effect of musical training for different harmonic phases, there was no significant difference in thresholds between sine and Schroeder phase, in contrast to the results of Houtsma and Smurzynski (1990). A possible explanation may be that we used a noise level high enough to mask distortion products, in combination with a low sensation level, which has been shown to lead to higher F_0DLs (Oxenham *et al.*, 2009). When the F_0DLs are high, spectral edge pitch may help in the discrimination task for the INT and UN conditions. This may explain the very small (or absent) benefit of musicians for the INT and UN conditions, as well as the absence of significant phase effects for the UN conditions (Oxenham *et al.*, 2009).

Overall, the findings of this study suggest that the F_0-discrimination performance of all listeners depends on sensitivity to TFS cues for complex tones containing low and intermediate numbered harmonics (Moore and Moore, 2003). Although limited by age, TFS cues were generally enhanced in musicians. This may be explained by enhanced neural synchrony in the brainstem of musicians (Parbery-Clark *et al.*, 2012), which could increase the sensitivity to small time differences and lead to a more accurate representation of pitch (Bianchi *et al.*, 2017). These findings suggest that although the sensory encoding of pitch cues was degraded in older and HI listeners, a benefit of musical training comparable to that of YNH listeners was still present and could account for improved encoding of TFS cues and F_0 discrimination. Hence, music-training paradigms in older listeners may be considered as a tool to improve auditory perceptual skills, although the effects may be different if musical training is applied later in life after hearing loss onset.

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