The role of harmonic resolvability for pitch discrimination

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Introduction

Pitch can be described as the perceptual correlate of the repetition rate of a sound stimulus. Pitch discrimination plays an important role when defining and differentiating our acoustic environment, especially concerning the perception of music or speech. One of the factors that might determine pitch discrimination performance is *resolvability*, the spectral separation of individual harmonics within the auditory system. As strong correlations between frequency selectivity and pitch discrimination have been observed [3, 6], resolvability may play an important role in pitch discrimination.

However, behavioral results have recently questioned this role of resolvability [1, 2]. Fundamental frequency difference limens (f_0 DLs) were measured for harmonic complex tones with all components presented to both ears and with even and odd harmonics presented to different ears. Additionally, complex tones containing a small mistuning (3 %) of the odd harmonics were tested [1]. The results showed that when alternating harmonics were presented to opposite ears, f_0 DLs improved, but that when mistuning the odd harmonics by a fixed percentage, performance was enhanced dramatically. It was suggested that a discrimination benefit from shifting the odd harmonics was not due to peripherally more resolved stimulus components but rather that a shift encouraged perceptual segregation based on inharmonicity. Therefore, f_0 discrimination might depend on auditory filter bandwidths but spectral resolution of individual harmonics may not be necessary for accurate f_0 discrimination, [1].

Because of this conflicting evidence about the extent to which resolvability affects pitch discrimination, the study mentioned above [1] was expanded here with a group of normal hearing (NH) musicians and non-musicians and with a group of hearing impaired (HI) test subjects. The aim was to further investigate the relationship between resolvability and good pitch discrimination. In addition, it was investigated whether HI listeners, for whom components are expected to be less resolved due to broader auditory filters, show lower thresholds for a dichotic presentation or when shifting the f_0 of the odd harmonics.

Methodology

In this experiment, f_0 DLs were measured as a function of f_0 in NH and HI listeners. The stimuli were 300 ms complex tones with equal-level and random-phase components and rise and fall ramps of 30 ms. They were bandpass filtered with lower and upper cut-off frequencies of 1.5 and 3.5 kHz, respectively. The low- and high-frequency slopes of the filter were set to 50 dB per octave. The tone complexes contained even and odd harmonics either from the same or from two different f_0s, giving a harmonic and a shifted condition. In the shifted condition, the f_0 of the odd harmonics ($f_{0,odd}$) was set 3 % higher than the f_0 of the even harmonics ($f_{0,even}$). The stimuli were presented either with all harmonic components to both ears (diotic) or even and odd components to opposite ears (dichotic). In dichotic presentation, even and odd harmonics were assigned randomly to right and left ears on a trial-by-trial basis. Overall, this yielded four conditions that were presented to the listener randomly: diotic and harmonic, diotic and shifted, dichotic and harmonic, and dichotic and shifted. The root-mean-square (RMS) amplitude of the combined even components was equalized across presentation intervals and the odd components were scaled to the same level per component as the even ones. To equalize the overall level, the RMS amplitude was set to be the same for all stimulus intervals. A random level perturbation was added to each interval, chosen from a uniform distribution of $\pm$ 2.5 dB. The f_0 was also roved from trial-to-trial in each run within a uniform distribution of $\pm$ 5 %. To mask distortion products, the complex tones were embedded in a threshold equalizing noise (TEN, [5]) filtered from 20 to 10000 Hz and presented diotically. For each test subject, the 0-dB sensation level (SL) reference was determined from the average detection threshold in TEN for 1.5, 2, and 3 kHz probe tones presented monaurally to the right ear. The level of each component of the complex tones was set to be 12.5 dB SL before bandpass filtering. For a TEN level of 55 dB per equivalent rectangular bandwidth (ERB), f_0s of 50, 125, and 200 Hz were tested.

For the HI test subjects the experiment was performed with a 55 dB/ERB TEN level or higher, depending on the hearing loss. To determine whether the noise level was above threshold, pure tone thresholds in quiet were measured monaurally at 1.5, 2, and 3 kHz for both ears. For test subjects exceeding 55 dB SPL, the TEN level was set to the highest threshold measured at either 1.5, 2, or 3 kHz for the particular ear. Again, the 0-dB SL reference was determined as the average detection threshold for 1.5, 2, and 3 kHz probe tones presented monaurally but measured in both ears. All component levels were then set to 12.5 dB SL.

Procedure

The stimuli were presented in a three alternative forced choice task (3-AFC) with an adaptive weighted up-down procedure [4] tracking the 75 % correct point on the psychometric function. Gaps of 300 ms separated the three intervals from each other. The background noise started 200 ms before the first interval and ended 100 ms after the last.

Two of the stimulus intervals contained a base f_0 and one was presented with a higher f_0 ($f_0 + \Delta f$). The listeners task was to identify the interval with the higher pitch. Feedback (wrong/correct) was given after each response. The initial Δf was 40 % of the base f_0 and the threshold was calculated as the mean from all values over the last 6 reversals.

Two hours of training were provided for each listener, after which three repetitions of the experiment were performed and used in data analysis. The subjects were seated in a sound-attenuating chamber and the stimuli were presented via Sennheiser HDA 200 headphones.

Listeners

The group of NH listeners contained 14 test subjects, six of them female. For each listener, all audiometric thresholds were 20 dB HL or less at octave frequencies between 0.125 and 8 kHz. The age range of the participants was 21-28 years (median: 25). Furthermore, six of the participants were musicians with at least 2 years of musical training.

The five HI listeners were chosen according to their audiogram, which indicated a sensorineural and symmetric hearing loss. Another criterion was that the audiometric thresholds did not exceed 70 dB HL in the frequency range between 1 and 4 kHz. The age range of the participants was 56-77 (median: 67) and two of the subjects were musicians.

Results

Normal-hearing listeners

The results for eight non-musicians and six musicians can be seen in figures 1 and 2, respectively. Squares indicate the diotic condition, circles the dichotic condition. Filled symbols represent a harmonic stimulus presentation while empty symbols stand for a condition with a shifted $f_{0,odd}$ of 3 %. The error bars depict the standard error.

Comparing the behavioral results of the current study

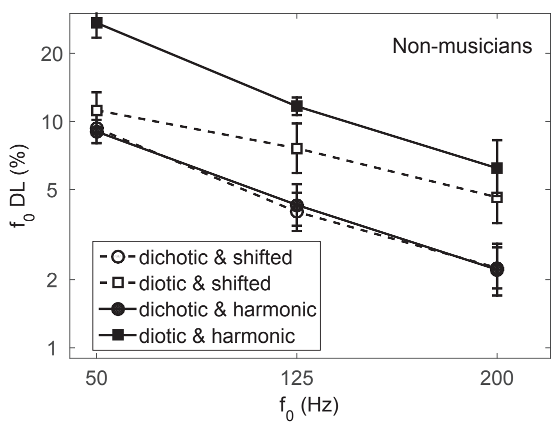

Figure 1: Mean results and standard error for 8 normal hearing non-musicians. Measured f_0 DLs are plotted as a function of f_0 for bandpass filtered tone complexes in 55 dB/ERB TEN. The complexes were tested in harmonic or in shifted conditions (odd harmonics shifted by 3 %) with diotic and dichotic stimulus presentations.

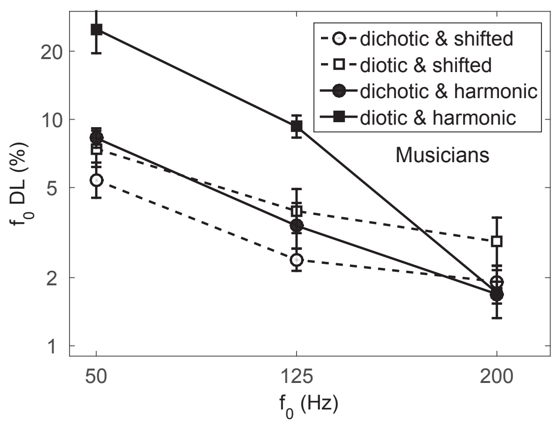

Figure 2: Mean results and standard error for 6 normal hearing musicians. Measured f_0 DLs are plotted as a function of f_0 for bandpass filtered tone complexes in 55 dB/ERB TEN. The complexes were tested in harmonic or in shifted conditions (odd harmonics shifted by 3 %) with diotic and dichotic stimulus presentations.

with previous findings [1], the range of obtained f_0 DLs was generally similar. Discrimination performance improved with f_0 and the strong improvement in f_0 DLs due to shifting the odd harmonics was reproduced, see fig. 1 and 2. However, several differences were observed with the results of [1] that are described in the following for each f_0 separately.

For stimuli with a low f_0 of 50 Hz, both experiments showed the same trend in f_0 DLs over the conditions. First, the diotic harmonic conditions led to highest (worst) f_0 DLs. Second, when introducing a shift of the odd harmonics, f_0 DLs improved significantly in the diotic and dichotic conditions. Third, when presenting the stimulus dichotically in the harmonic condition, a similar improvement to the shifted condition occured.

For an f_0 of 125 Hz, large differences compared to [1] can be seen. In the current study, the diotic harmonic condition showed worst f_0 DLs. The diotic shifted condition gave a benefit but f_0 DLs improved drastically for both dichotic conditions. In [1], the benefit from shifting the odd harmonics was much stronger for the diotic presentation than in this study. Additionally, [1] did not find the harmonic dichotic condition to be as beneficial as the shifted dichotic condition. For the musicians (fig. 2), a difference between both dichotic conditions can be observed as the shifted dichotic stimuli led to lowest (best) f_0 DLs.

For the stimuli with an f_0 of 200 Hz, the f_0 DLs in [1] were very similar across conditions. In the present experiment, a gap between the diotic and the dichotic conditions was apparent. Here, it is interesting to note that comparing the results of musicians and the non-musicians, different trends were found. In diotic harmonic condition, f_0 DLs were lower for musicians than for non-musicians for the f_0 of 200 Hz, see fig. 2.

Hearing-impaired listeners

For the HI listeners, the five subjects were divided into two groups. The first group contained test subjects with mild to moderate hearing loss and showed similar tendencies to NH listeners but with overall elevated f_0 DLs. For the second group, the hearing loss was more severe and f_0 DLs showed very different tendencies from those of the first group. The subjects whose results are shown in figures 3 (listener A, group 1) and 4 (listener B, group 2) were selected as they are representative of the trends observed for each group.

For listener A (fig. 3), similarly to NH listeners, discrimination improved with f_0, the diotic harmonic condition led to highest f_0 DLs, and introducing a shift in the dichotic condition resulted in lowest f_0 DLs. A possible explanation for the similarities to NH listeners is that the hearing loss of this subject was not as severe as for the other subjects. Additionally, listener A was the only subject where the background TEN did not exceed 55 dB/ERB for both ears. However, both the harmonic dichotic and shifted diotic presentations were not as beneficial as for NH listeners.

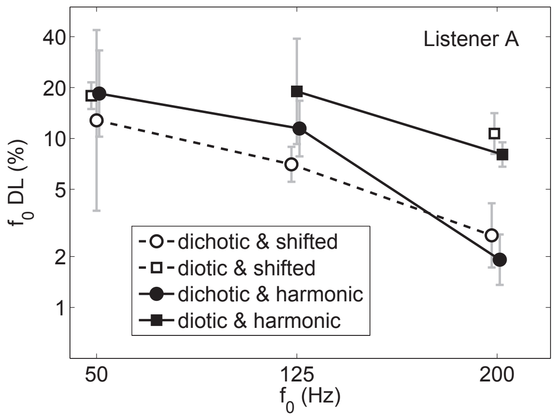

Figure 3: Mean results (symbols) and standard deviations (gray line) for hearing impaired listener A. Estimated f_0 DLs are plotted as a function of f_0 for bandpass filtered tone complexes in 55 dB/ERB TEN. The complexes were tested in harmonic or in shifted conditions (odd harmonics shifted by 3 %) with diotic and dichotic stimulus presentations.

For listener B (fig. 4), complex tones with an f_0 of 50 Hz led to lower f_0 DLs in the shifted conditions than the harmonic condition and to lower f_0 DLs than for NH listeners. For $f_0 = 125$ Hz, the f_0 DLs of the shifted conditions were slightly worse than in the harmonic conditions and at $f_0 = 200$ Hz the two dichotic conditions were worse than the two diotic conditions. The latter is quite remarkable as this trend is opposite to results of the NH group.

Discussion

Normal-hearing listeners

Experiments based on the study of [1] were conducted and results were compared to those of that study. The range of obtained f_0 DLs was similar and an effect of improved f_0 DLs when shifting the odd harmonics was observed.

However, one of the main findings of this experiment is that, for both harmonic and shifted conditions best performance (lowest f_0 DLs) was found for dichotic presen-

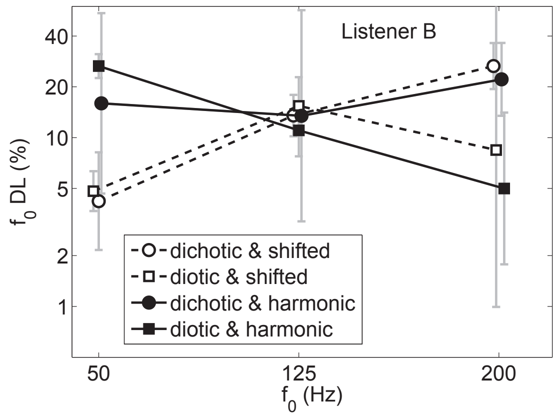

Figure 4: Mean results (symbols) and standard deviations (gray line) for hearing impaired listener B. Estimated f_0 DLs are plotted as a function of f_0 for bandpass filtered tone complexes in 56 dB/ERB TEN (right ear) and 58 dB/ERB TEN (left ear). The complexes were tested in harmonic or in shifted conditions (odd harmonics shifted by 3 %) with diotic and dichotic stimulus presentations.

tation. From this observation, an effect of peripheral resolvability cannot be ruled out completely as suggested by [1]. In their study, the harmonic dichotic condition was only as beneficial as shifting the odd harmonics at low f_0s (< 75 Hz). At medium and higher f_0s, introducing a shift led to a stronger improvement than a dichotic presentation.

Another important finding is that shifting the $f_{0,odd}$ gave a benefit in both the dichotic and the diotic conditions compared to the harmonic diotic condition when the f_0 is at 50 Hz. However, the shifted diotic condition was not as beneficial as the shifted dichotic condition for f_0s larger than 50 Hz. This observation is in contrast to [1] and supports a role of peripheral resolvability in pitch discrimination.

Hearing-impaired listeners

For the first group of HI listeners, f_0 DLs showed generally similar tendencies to NH listeners but with elevated thresholds (see listener A, fig. 3). The worsening of pitch discrimination can be connected to broader auditory filters compared to NH listeners. However, a clear improvement of performance by only shifting the odd harmonics, as it was found for NH listeners, was not apparent for this group of HI listeners: Even though the shifted dichotic condition led to lowest f_0 DLs, no continuous discrimination benefit was obtained for the shifted diotic condition.

For the second group (see listener B, fig. 4), a benefit from shifting the odd harmonics was observed for stimuli with $f_0 = 50$ Hz in diotic and dichotic presentations. However, for these listeners, the benefit from shifting the $f_{0,odd}$ vanished for higher f_0s. Additionally, for complex tones with an f_0 of 200 Hz, both diotic conditions showed an even better performance than the dichotic ones. At first sight, this is remarkable as for the NH listeners the dichotic conditions gave a benefit.

However, temporal modulation transfer functions (TMTFs) and f_0 DLs were measured for the same HI

listeners in another study [6], where the comparison of TMTFs and f_0 DLs suggested that the complex tones were unresolved at all f_0s for the listeners of group 2, such that pitch discrimination relied exclusively on temporal envelope coding. Improved pitch discrimination abilities for low f_0s might therefore be linked to an enhancement in envelope coding compared to NH listeners. This is comparable to the improved f_0 DLs in the shifted conditions of the present study. In addition, the TMTFs indicated a "sluggishness" for high f_0s, i.e. a limitation of the auditory system in coding fast amplitude fluctuations [6]. This can be related to the reduced performance for the dichotic conditions for complex tones with $f_0 = 200$ Hz. If the information from both ears is processed separately, the f_0 is doubled and the envelope fluctuations become faster wherefore f_0 DLs increase.
For HI listeners, the auditory filters are broader than for NH listeners. Depending on the hearing loss, the frequency spacing between the harmonics must be larger for a partial to be resolved. From the results found in this experiment and the measured TMTFs it can be concluded that, for the HI listeners of group 1, the stimuli still contained some resolved components but less than for NH listeners leading to similar but elevated thresholds. For the HI listeners of group 2, the hearing loss was more severe and the auditory filters are broader than compared to the HI listeners of group 1. The presented stimuli had no components that could be resolved and pitch discrimination probably relied on temporal envelope coding.
Finally, it is worth noting that a benefit from shifting the odd harmonics was found only at low f_0s where the use of place cues is unlikely, in HI but also in NH listeners. Therefore, this benefit might be explained by a change in temporal cues rather than a change in place cues or resolvability.

Summary and Conclusion

In this experiment, fundamental frequency discrimination was measured for NH and HI listeners. Bandpass-filtered harmonic complex tones were used to determine f_0 DLs as a function of f_0, based on an earlier study [1]. For NH listeners, measured thresholds became worse when harmonics below the 10th were no longer present in the stimulus. Presenting the even and odd harmonics to different ears led to peripherally resolved stimuli and improved discrimination performance. When mistuning the odd harmonics by a fixed percentage, performance improved as well but did not get better than with odd and even harmonics presented to different ears. These results suggest that (peripheral) resolvability might still play a role for pitch discrimination. Additionally, a benefit from a dichotic presentation suggests that the information between the ears is processed separately, at least to some extent.
The HI listeners were divided into two groups. The first goup had only a mild to moderate hearing loss and showed similar trends to NH listeners but with a worsened overall performance. The second group of HI listeners showed a more severe hearing loss and supposedly broader auditory filters compared to the first group. For these listeners a better pitch discrimination than NH listeners was observed at low f_0s, probably due to an enhancement of envelope processing. For higher f_0s pitch discrimination worsened showing the opposite trend to NH listeners. Here, the sluggnishness of the auditory system that limits envelope coding at high modulation rates may explain poorer performance in the dichotic condition at high f_0s. As the f_0 is doubled when presenting even and odd harmonics to different ears this suggests again that the auditory system does separate the information coming from the two ears.
As an outlook, further measurements may help to clarify the following points. As thresholds change when stimuli are presented dichotically compared to a diotic presentation for NH and HI listeners, these conditions need to be investigated further to determine to which extend the auditory system is able to process information from both ears separately. Moreover, as a benefit from shifting the odd harmonics occurred, a more detailed analysis of whether the resolution of the stimulus components is affected by a shift would be necessary to clearly rule out spectral cues being the cause of this benefit. Finally, further data should be collected in more HI listeners to relate pitch discrimination performance to the availability and accuracy of place and temporal envelope cues in individual listeners.

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