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Clinical Assessment of Pitch Perception

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Objective: The perception of pitch has recently gained attention. At present, clinical audiologic tests to assess this are hardly available. This article reports on the development of a clinical test using harmonic intonation (HI) and disharmonic intonation (DI).
Study Design: Prospective collection of normative data and pilot study in hearing-impaired subjects.
Setting: Tertiary referral center.
Patients: Normative data were collected from 90 normal-hearing subjects recruited from 3 different language backgrounds. The pilot study was conducted on 18 hearing-impaired individuals who were selected into 3 pathologic groups: high-frequency hearing loss (HF), low-frequency hearing loss (LF), and cochlear implant users (CI).
Intervention(s): Normative data collection and exploratory diagnostics by means of the newly constructed HI/DI tests using intonation patterns to find the just noticeable difference (JND) for pitch discrimination in low-frequency harmonic complex sounds presented in a same-different task.
Main Outcome Measure(s): JND for pitch discrimination using HI/DI tests in the hearing population and pathologic groups.
Results: Normative data are presented in 5 parameter statistics and box-and-whisker plots showing median JNDs of 2 (HI) and 3 Hz (DI). The results on both tests are statistically abnormal in LF and CI subjects, whereas they are not significantly abnormal in the HF group.
Conclusion: The HI and DI tests allow the clinical assessment of low-frequency pitch perception. The data obtained in this study define the normal zone for both tests. Preliminary results indicate possible abnormal TFS perception in some hearing-impaired subjects. **Key Words:** A§E—Clinical—Perception—Pitch—Temporal fine structure.
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Pitch is an attribute of sound that has been shown to be important for both music perception and the quality of speech perception (1,2). By allowing us to order sounds on the low-high dimension, pitch carries essential information about the tonality and melody in music and about the linguistic context of words and sentences in spoken language (e.g., clause typing) (3,4). Like loudness relates to sound intensity, pitch relates to the frequency content of sounds. In daily life, the relevant cues for voicing, melody, intonation, and other musically and linguistically important percepts are conveyed by relatively low frequency pitch, relating mainly to the fundamental frequency or F0. The fundamental frequencies of several competing voices in a noisy environment, for example, allow us to distinguish between separate speakers (5). The way the cochlea codes spectral content of sound can be explained by 2 underlying mechanisms, place coding and phase locking. Both are complementary and overlapping. It is believed that for low-frequency signals, such as the fundamental frequencies of human voices, phase locking of the temporal pattern of nerve responses to the temporal fine structure of the signal is the more dominant cue for conveying pitch. With increasing frequencies, this neural synchronicity becomes more difficult to be maintained. Place coding then comes gradually into play and replaces the phase locking as mechanism for spectral discrimination (2).

In the clinic, hearing assessment often is restricted to measures of detection (e.g., tone audiometry) or identification (e.g., speech audiometry). Clinical tests allowing more fine-grained analysis of the coding of the different components of sound, like spectral discrimination, are rare, and to the best of our knowledge, no tests exist that focus on the capacity of the auditory system to discriminate pitch. The absence of such tests may not have been a problem so far. However, with the emergence of new therapeutic options for sensorineural hearing loss, like cochlear implants, electroacoustic stimulation, or even molecular or genetic therapies, the need for such tests may

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increase. For instance, cochlear implants (CIs) attempt to restore the tonotopic organization of the inner ear by inserting an array of electrode contacts into the cochlea. This way, the place coding mechanism of the auditory system is partially restored. We think that the A§E spectral discrimination task is helpful in assessing the spectral discrimination, and we use it daily in the selection of CI candidates and the programming of CI processors (6). However, this test uses unfiltered phonemes as test items, and it therefore does not allow focusing on low-frequency discrimination. Poor low-frequency pitch perception may play a role in a number of frequently encountered complaints by current CI users, like poor music appreciation or poor spatial separation of multiple speakers (5,7). A clinical test focusing on pitch discrimination could potentially document and measure this. This is merely one illustration of the need of clinical tests to assess the coding of low-frequency pitch.

This article presents the development of such clinical tests to assess the coding of low frequency pitch. They are believed to be relevant in gaining more detailed insight in the coding of sound by the unaided or aided auditory system, and they are expected to be indicative for the capability of the inner ear to use its phase-locking mechanism. Two distinct tests were designed: harmonic intonation (HI) and disharmonic intonation (DI). They both use low-frequency harmonic complexes presented in a same-different paradigm, to find the just noticeable difference (JND) for pitch discrimination in individual subjects. Intonation patterns are applied to the stimuli to maximize focus on temporal processing. For both tests, the construction of stimulus material, test-retest validation, normative data, and preliminary results in a number of hearing-impaired subjects and cochlear implant users are presented.

MATERIALS AND METHODS

In each trial of both the HI and DI tests, 2 stimuli are presented consecutively, one of which has an intonation, whereas the other one does not. The test task is a same-different discrimination task.

The nonintonating stimulus that is one of both stimuli in all trials is a harmonic complex signal having a fundamental frequency (F0) of 200 Hz and 3 higher harmonics (with frequencies of 2F0, 3F0, and 4F0). The intensities of the harmonics decrease in comparison with F0 (−6 dB at 400 Hz, −12 dB at 600 Hz, and −18 dB at 800 Hz). A white noise was added to the stimuli (signal-to-noise ratio, +10.9 dB) to make them sound more natural and easy to listen to. Both in the HI and the DI test, the nonintonating sound is presented in contrast to an intonating sound. The intonating sounds used in the HI test feature a frequency sweep of all harmonics (including F0) from NF0 to N(F0 +ΔF), with N ranging from 1 to 4. In the DI test, however, the intonating sounds feature a sweep of the fundamental frequency only (F0 to F0 + ΔF), whereas the higher harmonics are kept fixed at their initial frequency, as shown in Figure 1. As a consequence, the harmonic separation of partial tones is distorted by the sweep, hence a disharmonic (or dissonant) intonation. For both stimulus types, the sweep is linear and introduced at 330 ms after the start of the signal. The sweep duration is 120 ms, and the total signal duration is 600 ms. The timings of the intonation were chosen to resemble the intonation pattern that is used in clause typing to form a question.

Each trial thus consists of 2 consecutive stimuli separated by a 500-ms silence. One of 2 stimuli is the nonintonating sound, whereas the other sound is the intonating signal featuring a pitch change ΔF (imposed by either a harmonic intonation in the HI test or a disharmonic intonation in the DI test). The order of stimuli within a trial is randomized. Stimuli are presented to the listener in a same-different task. The listener indicates whether he perceives a difference between the presented sounds. A JND (also called *difference limen* or *threshold*) is sought using an adaptive staircase procedure. The details of this procedure are described elsewhere (8). Briefly, after a training session to make the listener familiar with the task and the test sounds used, the test starts with a large ΔF of 41 Hz. In case the test person discriminates the 2 sounds, ΔF is reduced, and vice versa, according to a dithered one-up one-down procedure converging to the 50% point on the psychometric curve. Internal controls and stochastic processes are implemented to enhance the reliability and to sanction and correct for false-positive responses. Intensity roving (±2 dB) is applied to discourage listeners to use any possible loudness cues to discriminate between sounds. Reaction times are recorded on every trial, and total test duration is measured.

Initially, the stimulus domain was constructed to contain 41 stimulus levels ranging from the 200 Hz reference to a 350 Hz

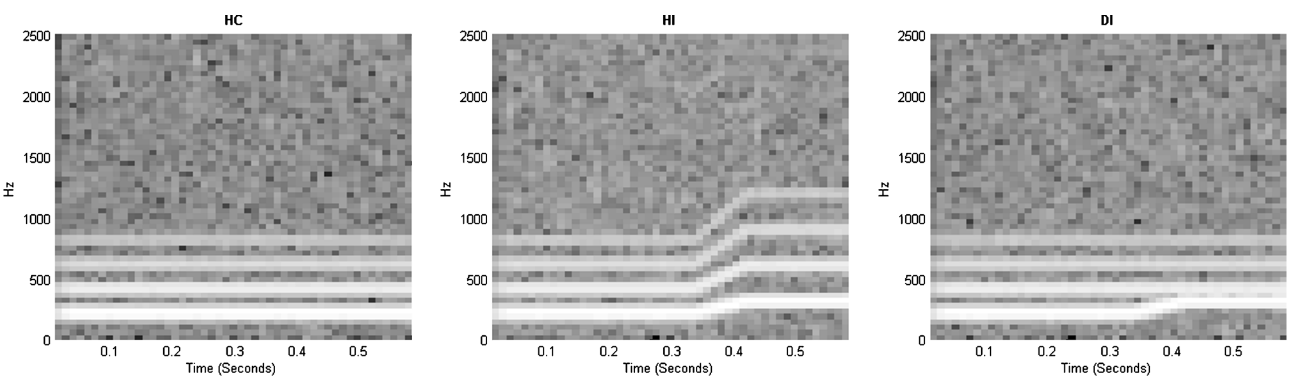

FIG. 1. Spectrograms of the stimuli: on the left, the nonintonating 200-Hz harmonic complex; in the middle, the harmonic intonating sound with all harmonics sweeping from N*200 to N*294 Hz; and on the right, the disharmonic intonation, with only the fundamental frequency sweeping from 200 to 294 Hz, keeping higher harmonics fixed at their initial frequency.

maximum. Interlevel intervals were decreased stepwise from a 1/12 semitone interval in the 200 to 208 Hz range over a 1/6 semitone interval in the 208 to 229 Hz range to a 1/3 semitone interval in the 229 to 350 Hz range. To qualify the setup with the chosen stimulus domain as a robust and accurate measure of pitch perception, a test-retest validation was performed in 29 human subjects. The observed mean absolute difference (±SD) between test and retest was 0.043 (±0.032) semitones for HI and 0.043 (±0.63) semitones for DI. Based on this variability, the minimum interlevel interval for both tests was set to the 0.17 semitones, which represents the 97.5th percentile of the observed differences for the most variation-sensitive test (DI). The chosen minimum interlevel interval is expected to cause a test-retest variability of maximum 1 interval in 95% of test runs.

The new stimulus domain is depicted in Figure 2 and contains 36 stimulus levels ranging from the 200 Hz reference to a new 414 Hz maximum. The interlevel interval is kept constant at 1/6 semitones for levels up to 224 Hz, which is 2 semitones above the reference level. From there on, the interval increases linearly and with respect to the stimulus level. By decreasing accuracy at higher JNDs, it is expected that the average duration of the test is decreased, in particular when performed in hearing-impaired subjects. Based on the available stimulus levels, the algorithm sets the initial level to 241 Hz and applies an initial step size of 9 levels. Whenever the procedure was unable to converge to a threshold (e.g., the subject's JND is not in the range of the stimulus domain), a JND of 220 Hz was coded for the current analysis. Both HI and DI tests are implemented in the A§E psychoacoustic test battery (6,9).

The new test setup was then used to estimate JNDs for pitch perception in the normal-hearing population. Ninety subjects aged between 18 and 53 years were recruited from 3 different language groups (Dutch, Italian, and Romanian). All subjects had normal audiometric thresholds (<20 dB HL at octave frequencies between 125 and 8,000 Hz) at both ears and reported no otologic history. Written informed consent was obtained for all participants. Both HI and DI test results were compared across language groups (Mann-Whitney *U* test). Results from different languages were then pooled to calculate the 95% confidence interval and to extract normative data for both tests.

To explore the practical use of the intonation tests, a pilot study was set up with 18 hearing-impaired individuals who were selected into 3 pathologic groups of 6 subjects each: 1) high frequency hearing loss (HF) featuring audiometric thresholds (better ear) better than 25 dB HL at 250 and 500 Hz and worse than 40 dB HL at 2, 4, and 8 kHz (testing was done in the unaided condition); 2) low frequency hearing loss (LF) featuring audiometric thresholds (better ear) worse than 35 dB HL at 500 Hz and better than the threshold at 500 Hz at 2 and 4 kHz, and 3) cochlear implant users (CI) featuring a normal cochlear anatomy and unaided audiometric thresholds of more than 80 dB HL at the better ear, having been implanted (with full electrode insertion) with their first and only CI more than 6 months before the start of the experiments. Three of them were using the AB HiRes90k implant with Harmony processor (Advanced Bionics LLC, Valencia, CA, USA), the other 3 were using the Cochlear Nucleus 24 with Freedom processor (Cochlear Ltd., Sydney, Australia). The presentation level was 20 dB SL with a minimum of 70 dB SPL. Nonparametric statistics (box and whisker plots, Kruskall-Wallis, and Mann-Whitney *U* tests) were used to display the results and to compare the results between the 3 pathologic groups and between each group and the hearing subjects and paired nonparametric statistics (Wilcoxon test) to compare the differences between HI and DI results within subjects.

RESULTS

Figure 3 shows the results of normal-hearing subjects for HI (left hand side) and DI (right hand side). No statistically significant differences were found between different language groups, except for the HI results between Dutch (median JND, 1.5 Hz) and Italian (median JND, 2.5 Hz) speakers ($p < 0.01$). This difference of 0.09 semitones is clinically and linguistically irrelevant. Therefore, data from different language groups were pooled to obtain normative data, which are depicted in black (Fig. 3). The HI test results (median JND, 2.0 Hz) seemed to be significantly different from the DI test results (median JND, 3.0 Hz) ($p < 0.001$).

Figure 4 shows the results of the pathologic groups. The HF group showed median JNDs of 2.0 Hz for HI and 5.0 Hz for DI with the majority of subjects having scores within the reference range. However, the LF and CI groups showed significant differences ($p < 0.01$) in both HI and DI tests when compared with the normative

FIG. 2. The possible stimulus levels in both versions of the tests. The initial stimulus domain (*crosses*) featured a stepwise increase in interlevel interval going up to a maximum of 350 Hz (i.e., 9.7 semitones above the reference stimulus level of 200 Hz). The domain after test-retest validation (*triangles*) features a constant interlevel interval of 1/6 semitones for levels up to 224 Hz (i.e., 2.0 semitones above reference). From there on, the interlevel interval increases linearly at a ratio of 1/12 semitone per 1 semitone increase in stimulus level up to a 414 Hz maximum (i.e., 12.6 semitones above reference).

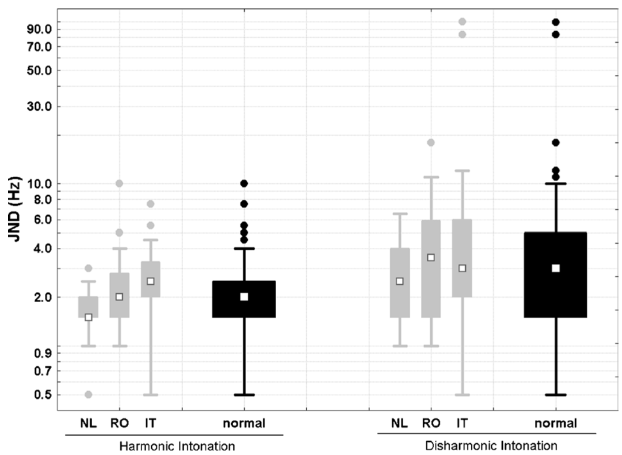

FIG. 3. The results in hearing subjects on the HI (*left graphs*) and the DI (*right graphs*) test as box and whiskers plots, where the *central dot* represents the median, the *box* the interquartile region, the *whiskers* the range, and the *separate dots* the outliers). The results for each language group are depicted in gray (NL: Dutch, RO: Romanian, IT: Italian) and the pooled results in black.

data. The LF group obtained median scores of 54.0 and 94.0 Hz and the CI group, 7.5 and 158.5 Hz, on HI and DI, respectively. Across all runs of both HI and DI, the average (±SD) test duration was 144 seconds (±105 s).

DISCUSSION

The purpose of the harmonic and disharmonic intonation tests is to provide a clinical instrument to evaluate the spectral discrimination of the auditory system in the low-frequency range. They assess the perception of pitch changes in low-frequency complex tones. Two particular but inseparable peripheral auditory mechanisms are believed to lie at the origin of the spectral discriminative power of the cochlea. One of them is based on place of excitation (tonotopy) and conveys intonation through a spatial alteration of the population of active nerve fibers. The other is a time-based mechanism (phase locking) that locks onto the TFS of the signal to keep the nerve firings in sync with the fluctuations of sound pressure in time and conveys intonation by changing the auditory nerve fibers' firing rate, keeping it in pace with the instantaneous frequency of the signal. Although many experiments have indicated that the contribution of each of these mechanisms to the total of useful information that is centrally processed may vary according to the nature of the signal, no single experiment exists to isolate one of 2 mechanisms completely. Nonetheless, it is believed that in low frequencies, phase locking is the more important mechanism for conveying pitch.

The HI and DI tests were designed to investigate pitch perception in a clinical situation. When comparing the stimuli, it is seen that the cue in HI is more salient: all harmonics are swept together with the fundamental. It is reasonable to assume that both place and time-based codes contribute to the accurate detection of this kind of intonation. However, in the DI stimuli, it is only the fundamental frequency that shifts. Looking at the critical bandwidth of auditory filters, it seems impossible to transfer an intonation as subtle as a few hertz in the 200-Hz region by a place-based code (10). In consequence, time-based codes are likely to dominate the accurate detection of this kind of intonation. In theory, keeping the higher harmonics fixed while the fundamental sweeps causes beating, and this may introduce a new cue that could bias the results. Beating occurs when 2 sound waves of different frequency are presented simultaneously. This causes a modulation that is the result of the alternating constructive and destructive interference between the waves. However, this possible bias only comes into play for JNDs much higher than a couple of hertz. The beat frequency is equal to the absolute value of the difference in frequency of the 2 waves. So for instance, with F1 = 200 Hz and F2 = 320 Hz, the beat frequency will be |200–320| = 120 beats per second (bps). In our DI test, beating occurs when F0 interferes with the stationary 400-Hz harmonic. Hence, with F0 = 202.5 Hz, the beat frequency is |400–202.5| = 197.5 bps. However, temporal modulation transfer functions are known to be low pass with a cutoff frequency near 70 bps for normal-hearing listeners (11). This indicates that a beat frequency of 192.5 bps could not be a cue to distinguish 2 signals. Temporal beatings in the DI stimulus can only serve to distinguish a tone with a stationary F0 of 200 Hz from one with a gliding F0 from 200 to 330 Hz or higher. However, then it is no longer relevant for the clinical interpretation of the test results. As shown, JNDs above 4 or 10 Hz are outside the clinical normal zone.

Another possible bias in the DI test results could come from the dissonance or loss of harmony in the signal that causes the percept of a split tone and a severely changing waveform that could lead to a lower JND. However,

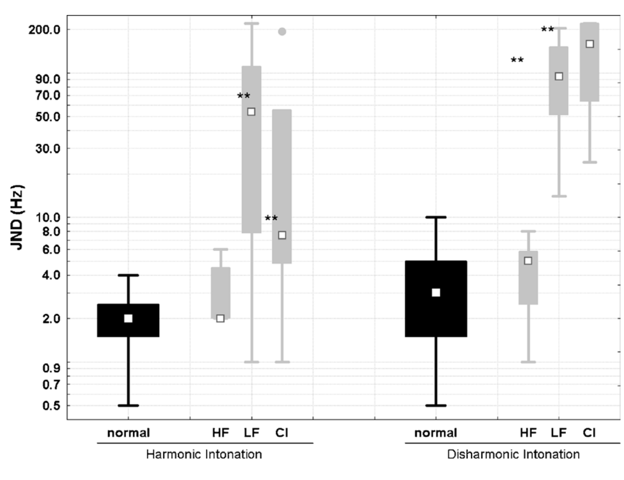

FIG. 4. The HI (*left graphs*) and DI (*right graphs*) results of the pilot study in subjects with hearing loss (see legend to Fig. 3 to understand the box and whisker plots). HF, high-frequency hearing loss; LF, low-frequency hearing loss; CI, cochlear implant users; and normal, the normal data (Fig. 3).

the results show that listeners are less sensitive to this loss of harmony than they are to the harmonic intonation. In normal-hearing subjects, differences between HI and DI, although statistically highly significant ($p < 0.001$), are so small (1 Hz) that they are unlikely to be clinically relevant.

In conclusion, it seems fair to say that both tests are easily performed in normal-hearing subjects, that the results are in line with earlier findings of JNDs for pitch changes, which are approximately between 1 and 4 Hz in the 200-Hz range and that the 2 tests do not assess fully identical psychoacoustic phenomena.

In addition, no relevant differences were found between language groups. We wanted to make sure that the normative data were not biased by the linguistic background of the listener. As said, pitch is used to convey linguistic information, but the importance of it can be different in different languages. For instance, the perception of syllable prominence in Dutch is predominantly cued by pitch and, to a lesser degree, by syllable duration, whereas in Italian, it is the other way around (12,13). It would be conceivable that Dutch listeners therefore have better acuity for pitch than Italian speakers. Because no differences were found between the Germanic and Romance language used, the tests seem largely language independent and applicable in different language groups.

The adjusted stimulus domain (after validation) is expected to cause a test-retest variability less than 1 interlevel interval, which adds to the robustness of the tests. Test durations measured indicate that, on average, HI and DI together can be performed in a single subject in less than 5 minutes. Together with the included training mode, this makes that the tests are well feasible in clinical practice.

Once a test is feasible in clinical practice and normative data have been obtained, the next step is to evaluate whether it is relevant in diagnostic, that is, pathologic situations. Although this is beyond the scope of the present article, preliminary results have been obtained in different groups with abnormal hearing. Although the numbers are too low to draw any robust conclusions, remarkable differences between results on HI and DI seem to exist in these groups.

The results of the CI group show that the majority of these subjects are performing reasonably well on the HI task, presumably because they are still able to use the place cue caused by all harmonics sweeping to detect pitch changes. On the DI task, the only spectral cue consists of the 200 Hz component shifting. As current CI devices are mainly tonotopically organized and have a limited number of electrodes, it is not likely that a subtle change in a single-frequency component causes a different electrode to be stimulated (14). The frequency bandwidth of the most apical channel was 250 to 416 Hz for the AB device and 188 to 313 Hz for the Nucleus device. Because no or only limited TFS is conveyed within one spectral band, the fundamental frequency needs to be analyzed into a different spectral band (causing a change in the physical stimulation site) for its sweep to be detected. As said before, high stimulus levels (ΔF, >150 Hz) also cause temporal beatings in the DI signal that may serve as cue for CI users to discriminate between sounds. This hypothesis is in line with the high JNDs on the DI test observed in the CI group (median JND, 158.5 Hz).

The different JNDs for HI and DI in the LF group could be attributed to the fact that the loss of audibility in the low-frequency region also impacts the spectral discrimination within this region. In general, this is attributed to the broadening of auditory filters as a result of malfunctioning hair cells. As the concept of filter bandwidth is not exclusively built on either place- or time-based coding, broadening may result from deficiencies in either or both of them. However, as discussed in the introduction, it is reasonable to assume that temporal coding is dominant in the DI task. Although speculative at this stage, it seems appealing to consider that this test might distinguish patients with perceptive hearing loss

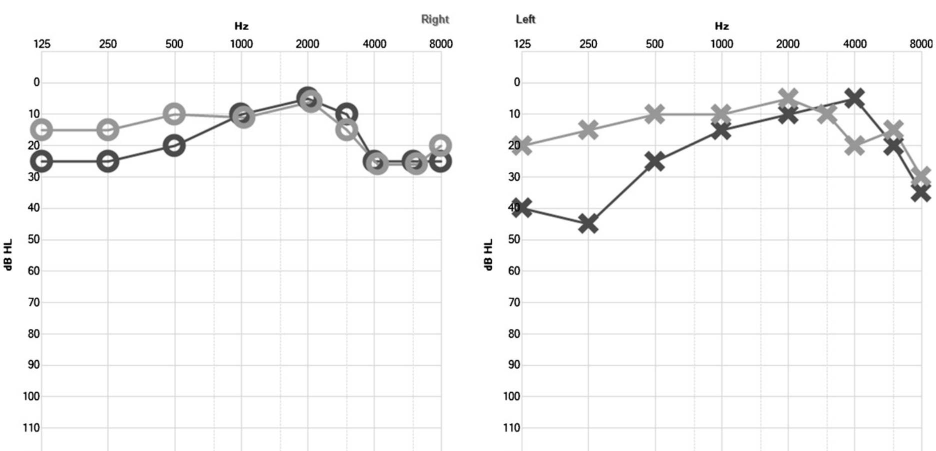

FIG. 5. The musician's audiometric thresholds for right (*left graph*) and left (*right graph*) ears at different points in time. The *dark gray curves* show thresholds at initial measurement (T0). The *light gray curves* show thresholds measured 4 months later (T0+4).

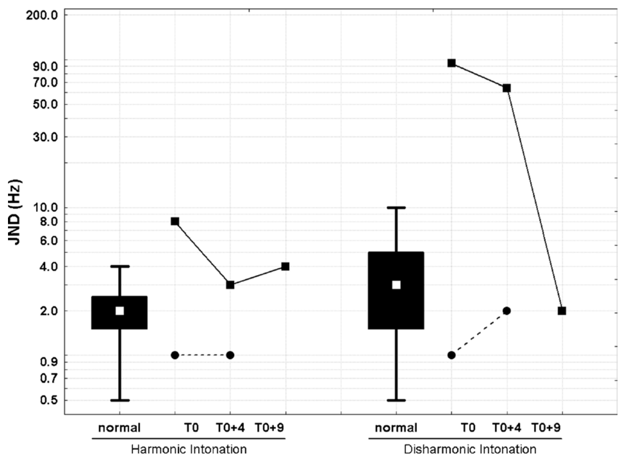

FIG. 6. The HI (*left graphs*) and DI (*right graphs*) results for both the left ear (*squares*) and the right ear (*dots*) of the musician at different points in time and in comparison with normal data. The results for the left ear show normalization of HI after 4 months (T0+4) and of DI after 9 months (T0+9).

who have good low-frequency TFS coding (phase locking) from others who have not.

An additional illustration comes from 1 particular subject having a low-frequency hearing loss, not included in the LF group. This subject was a professional musician who experienced episodes of dizziness, loss of equilibrium, and left-sided tinnitus since more than 6 months. He presented with recently developed hearing loss, distorted sound perception, and fullness at the left ear. Pure tone audiogram showed a low-frequency perceptive hearing loss, mainly at the left side (Fig. 5). He showed abnormal test results on both the HI and the DI test (Fig. 6). He was given medical treatment for Ménière's disease (betahistine and antidepressants) for 4 months, and when he returned, the audiometric thresholds had normalized (Fig. 5). Still, he felt unable to take up work again because, as a professional musician, he reported not to be able to follow the tone of his fellow musicians. When asked to specify, he said that ''the harmonics sounded too loud, while the ground tone seemed to be missing.'' The test showed that the HI result had normalized, whereas the DI result had remained abnormal (Fig. 6). Five months later, the man returned with the message that he had taken up work again and that, subjectively, the symptoms had disappeared. Test results confirmed normalization of the DI result as can be seen in Figure 6.

In conclusion, the HI and DI tests address the need for a more fine-grained and targeted clinical evaluation of the cochlear function. They provide clinicians with an instrument to assess the perception of low-frequency pitch perception, which is particularly important for understanding speech in multi-talker situations and also music appreciation. The tests have been shown to be clinically feasible with limited test duration and robust results. They also have been shown to be relevant because they are able to distinguish between different subpopulations and among individuals within subpopulations. This indicates that useful information could be extracted from application of the tests, and it is anticipated that they will enable clinicians to explore different pathologic conditions and that they may become instrumental in both diagnostic and therapeutic applications. They have been implemented in the A§E2009 psychoacoustic test suite (http://www.otoconsult.com) and are available for further exploration and clinical use (15–17).

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