The relationship between frequency selectivity and pitch discrimination: Sensorineural hearing loss

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This study tested the relationship between frequency selectivity and the minimum spacing between harmonics necessary for accurate f_0 discrimination. Fundamental frequency difference limens (f_0 DLs) were measured for ten listeners with moderate sensorineural hearing loss (SNHL) and three normal-hearing listeners for sine- and random-phase harmonic complexes, bandpass filtered between 1500 and 3500 Hz, with f_0's ranging from 75 to 500 Hz (or higher). All listeners showed a transition between small (good) f_0 DLs at high f_0's and large (poor) f_0 DLs at low f_0's, although the f_0 at which this transition occurred ($f_{0,\mathrm{tr}}$) varied across listeners. Three measures thought to reflect frequency selectivity were significantly correlated to both the $f_{0,\mathrm{tr}}$ and the minimum f_0 DL achieved at high f_0's: (1) the maximum f_0 for which f_0 DLs were phase dependent, (2) the maximum modulation frequency for which amplitude modulation and quasi-frequency modulation were discriminable, and (3) the equivalent rectangular bandwidth of the auditory filter, estimated using the notched-noise method. These results provide evidence of a relationship between f_0 discrimination performance and frequency selectivity in listeners with SNHL, supporting "spectral" and "spectro-temporal" theories of pitch perception that rely on sharp tuning in the auditory periphery to accurately extract f_0 information.
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I. INTRODUCTION

Harmonic sounds are ubiquitous in the natural environment. The pitch of such sounds, usually corresponding to the fundamental frequency (f_0), is a useful attribute in an everyday listening environment. For example, pitch can convey musical melody, prosody in running speech, and linguistic information in Asiatic tonal languages. Pitch information can also provide a cue for the segregation of simultaneous talkers (e.g., Darwin and Hukin, 2000), thus aiding speech intelligibility in complex environments.

Listeners with sensorineural hearing loss (SNHL) are often faced with an impaired ability to discriminate the f_0 of complex sounds (Hoekstra and Ritsma, 1977; Hoekstra, 1979; Moore and Glasberg, 1988; 1990a; Moore and Peters, 1992; Arehart, 1994; Moore, 1995; Arehart and Burns, 1999; Moore and Moore, 2003; for a recent review, see Moore and Carlyon, 2005). The mechanisms underlying the pitch processing deficit that accompanies SNHL remain poorly understood. One possible cause is the reduction in peripheral frequency selectivity that often accompanies SNHL (Glasberg and Moore, 1986). "Spectral" (e.g., Goldstein, 1973; Wightman, 1973; Terhardt, 1974; 1979) and some "spectro-temporal" (e.g., Shamma and Klein, 2000; Cedolin and Delgutte, 2005) models of pitch are based on the assumption that individual harmonics of a complex tone must be resolved within the peripheral auditory system for the f_0 to be successfully extracted (for a recent review, see de Cheveigné, 2005). These models predict that reduced harmonic resolvability in listeners with SNHL due to the broadening of peripheral filters (e.g., Tyler *et al.*, 1983; Glasberg and Moore, 1986; Moore *et al.*, 1999) should impair pitch processing.

Certain results in normal-hearing (NH) listeners support the role of frequency selectivity and harmonic resolvability in f_0 discrimination. A number of studies have found that f_0 difference limens (DLs) increase substantially as the lowest harmonic number present in the stimulus increases beyond about 10 (Hoekstra, 1979; Houtsma and Smurzynski, 1990; Shackleton and Carlyon, 1994; Bernstein and Oxenham, 2003; 2005; 2006; Moore *et al.*, 2006). The transition from good to poor f_0 discrimination appears to correspond reasonably well with the point at which individual harmonics can no longer be heard out reliably (Bernstein and Oxenham, 2003), and the point at which the phase relation between components begins to affect f_0 DLs (Houtsma and Smurzynski, 1990; Bernstein and Oxenham, 2005), although the estimated limit of resolvability varies somewhat, depending on the method used (Plomp, 1964; Moore and Ohgushi, 1993; Shackleton and Carlyon, 1994; Moore *et al.*, 2006). Furthermore, our companion paper (Bernstein and Oxenham, 2006) found that the increase in auditory filter bandwidths at high

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stimulus levels in NH listeners is accompanied by a shift in the transition point between good and poor f_0 discrimination towards higher f_0's (or lower harmonic numbers), as would be expected if low f_0 DLs required the presence of resolved harmonics.

Several studies have specifically investigated the relationship between frequency selectivity and f_0 discrimination in listeners with SNHL, but none has identified a strong correlation between the two (Hoekstra, 1979; Moore and Glasberg, 1990a; Moore and Peters, 1992). Moore and Glasberg (1990a) measured f_0 discrimination in listeners with unilateral SNHL for harmonic complexes containing both low- and high-order harmonics (1-12) and for complexes containing only high-order, less well resolved harmonics (6-12). They also estimated frequency selectivity by measuring auditory filter shapes (Glasberg and Moore, 1986). No significant correlation between frequency selectivity and f_0 discrimination was observed, although none of the listeners with poor frequency selectivity showed normal f_0 discrimination. In a related study, Moore and Peters (1992) investigated frequency selectivity and f_0 discrimination in both young and elderly NH and hearing-impaired (HI) listeners. While they found both reduced frequency selectivity and reduced f_0 discrimination performance for many of the HI listeners, there was only a weak correlation between the two measures.

Hoekstra (1979) and Hoekstra and Ritsma (1977) also measured f_0 discrimination in listeners with hearing impairment believed to be of cochlear origin. They used harmonic complexes with a range of f_0's, bandpass filtered into a fixed spectral region. They found that f_0 DLs decreased with increasing f_0, but that the transition between small and large f_0 DLs occurred at higher f_0's for HI listeners. This result is consistent with the idea that listeners with SNHL require a larger spacing between components to yield resolved harmonics and therefore good f_0 discrimination. Although Hoekstra (1979) and Hoekstra and Ritsma (1977) estimated frequency selectivity using psychophysical tuning curves (PTCs) in a subset of the HI listeners, the number of listeners in this subset was too small to permit a correlational analysis of the relationship between f_0 discrimination and frequency selectivity. Nevertheless, Hoekstra and Ritsma (1977) noted that those listeners with abnormally high f_0 DL transition f_0's also demonstrated abnormal PTCs, suggesting a relationship between the two measures. Arehart (1994), who varied the number of the lowest harmonic present, also found that the transition between small and large f_0 DLs occurred at a lower harmonic number for listeners with SNHL than for normal-hearing listeners, but did not relate this measure to estimates of peripheral frequency selectivity.

The goal of current study was to test the hypothesis that the harmonic spacing at which f_0 DLs change from large to small is dependent on peripheral frequency selectivity. This study differs from previous investigations of the relationship between f_0 discrimination and frequency selectivity in that it (1) focuses on the point of *transition* between large and small f_0 DLs (Experiment 1), and (2) relates this transition to measures of frequency selectivity (Experiments 2 and 3) in a sufficiently large and diverse population of HI listeners to enable a correlational analysis. The harmonic complexes were filtered into a passband extending from 1500 to 3500 Hz. Single-frequency measures of frequency selectivity and frequency discrimination used a signal frequency of 1500 Hz. This value, representing the lower cutoff of the passband for the complexes, was selected because it was the point at which the harmonics within the complex should have been best resolved, and is likely to represent the upper limit of performance (Houtsma and Smurzynski, 1990).

II. EXPERIMENT 1: FUNDAMENTAL FREQUENCY DIFFERENCE LIMENS

A. Rationale

Experiment 1 measured f_0 DLs as a function of f_0 for harmonic complexes, bandpass filtered into a fixed spectral region, in listeners with SNHL. By investigating the dependence of f_0 DLs on harmonic resolvability while keeping the frequency region constant, this paradigm avoided a possible confounding factor of SNHL that varies across frequency regions, which might arise in a paradigm that keeps f_0 constant while varying harmonic number (e.g. Houtsma and Smurzynski, 1990; Bernstein and Oxenham, 2003). With this paradigm, it is possible that listeners could have tracked individual frequencies rather than the f_0 in the case of resolved harmonics (Houtsma and Goldstein, 1972). However, Moore and Glasberg (1990b) demonstrated that listeners tend to base their pitch comparisons on the missing f_0 rather than on the frequencies of individual resolved components, even in cases where it would be advantageous to ignore the missing f_0.

Harmonic stimuli were presented in both sine and random phase to give an estimate of harmonic resolvability based on the phase dependence of f_0 DLs. In NH listeners, the phase relationships between harmonic components have been shown to affect f_0 DLs for complexes containing only high-order harmonics but not for those containing low-order harmonics (Moore, 1977; Houtsma and Smurzynski, 1990; Bernstein and Oxenham, 2005). This result is generally interpreted in terms of harmonic resolvability. For high-order unresolved harmonics that interact within individual peripheral filters, the phase relationship between components affects the temporal envelope and therefore the pitch percept associated with these complexes. In contrast, low-order resolved harmonics do not interact appreciably within individual peripheral filters, so the pitch percept associated with these harmonics is not affected by phase manipulations.

B. Listeners

Ten listeners (four female) with SNHL participated in the study. Pure-tone audiograms were measured using an AD229e diagnostic audiometer (Interacoustics) and TDH39 headphones. Bone-conduction threshold measurements (Radioear B-71) verified that the hearing loss for each listener was sensorineural in nature, based on the absence of any air-borne gaps larger than 10 dB. All listeners had moderate (30–65 dB HL *re* ANSI-1996) losses at audiometric frequencies between 1.5 and 4 kHz,[1] the relevant frequencies for the stimulus frequency range (1.5–3.5 kHz) used in the study, with two exceptions where the hearing loss still fell within

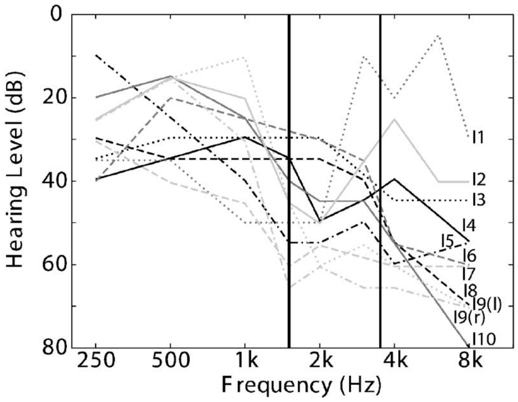

FIG. 1. Audiograms for the ten HI listeners (11 ears) who participated in the study. Vertical lines represent the 1.5–3.5 kHz stimulus region used in Experiments 1–3.

the specified range between 1.5 and 2 kHz, but was milder at higher frequencies.[2] A threshold equalizing noise (TEN) test for octave frequencies between 0.25 and 8 kHz verified the absence of "dead regions" in each listener (Moore *et al.*, 2000). Ages ranged from 27 to 78 years, with a mean of 49.7 and a median of 50.5 years. One HI listener (I6) was a trained musician with decades of musical experience, while the remaining HI listeners were nonmusicians. For each HI listener, measurements were made for the ear in which the hearing loss fell between 30 and 65 dB HL. If both ears met this criterion, the ear with the greater hearing loss was selected. Listeners with symmetrical losses were given their choice of test ear. One listener with an asymmetrical loss (I9) was tested in both ears. For simplicity, the two ears of this listener were treated as if they were from separate listeners [I9(1) and I9(r)], so that the total number of HI listeners was considered to be eleven. Audiograms for the 11 ears with SNHL are shown in Fig. 1, with vertical lines indicating the 1.5–3.5 kHz stimulus region tested in this study.

The study was designed to investigate correlations between f_0 discrimination and frequency selectivity within a group of listeners with SNHL, rather than to compare groups of NH and HI listeners. Nevertheless, three NH listeners (one female) were also included in the study to provide base line measurements. Normal-hearing listeners had audiometric thresholds of 15 dB HL or less *re* ANSI-1996 at octave frequencies between 0.25 and 8 kHz. The ages of the NH listeners were 19, 20, and 52 years. Each NH listener was tested with stimuli presented to the left ear. Two NH listeners (N1 and N2) were trained musicians with more than five years of formal training, while the third NH listener (N3) was a nonmusician. Table I provides audiological information for each NH and HI listener, as well as information regarding the stimulus level(s) tested in each of the three experiments (see Sec. II C 2). All listeners were paid for their time.

C. Method

The stimuli and methods for estimating f_0 DLs were similar to those used by Bernstein and Oxenham (2006), as described below.

1. Stimuli

Fundamental frequency DLs were measured as a function of f_0 for 500-ms (including 30-ms raised co-sine rise and fall ramps) random- and sine-phase harmonic complexes, bandpass filtered between 1.5 and 3.5 kHz, with 50 dB/oct. slopes. New phases were selected for each presentation of a random-phase complex. The filtering operation

TABLE I. Audiological and stimulus level information for the ten HI listeners (11 ears) and three NH listeners who participated in the study. (*) Measurements were made in both the left and right ears of listener I9. (**) Absolute thresholds were not measured in NH listeners using the adaptive technique and HD 580 headphones that were used in Experiments 1–3.

	Listener	Age	Sex	Test ear	Audiometric threshold at 1.5 kHz (dB HL) TDH 39	Max. adaptive threshold, 1.5–3.5 kHz (dB SPL) HD 580	TEN level (dB SPL/ ERB_N)
Hearing impaired	I1	29	F	R	50	49.3	50
	I2	58	M	L	45	46.3	50
	I3	67	M	R	30	36.5	50
	I4	58	F	L	35	44.8	50
	I5	52	M	R	55	48.2	50
	I6	78	F	R	27.5	47	50
	I7	27	M	L	60	57	60
	I8	33	M	L	35	50.2	50
	I9(l)*	46	F	L	45	58.7	60
	I9(r)*	46	F	R	65	61	62
	I10	49	M	L	40	46	50
Normal hearing	N1	19	M	L	−5	**	50,65
	N2	20	M	L	−2.5	**	50,65
	N3	52	F	L	5	**	50,65

was implemented in the spectral domain by first adjusting the amplitude of each sinusoidal component, and then summing all of the components together.

Random-phase harmonic complexes were chosen because they are known to yield very poor f_0 DLs (on the order of 5–10% of the f_0; Bernstein and Oxenham, 2003; 2005; 2006) when the harmonics are unresolved, thus producing a large f_0 DL difference between low and high f_0's and providing the best opportunity to observe the transition from large to small f_0 DLs. Sine-phase conditions were included to give an estimate of harmonic resolvability based on the phase dependence of f_0 DLs. At least nine f_0's were tested for each HI listener (75, 125, 150, 175, 200, 250, 325, 400, and 500 Hz). Higher f_0's (750 Hz and, in one case, 1500 Hz) were tested for some HI listeners for whom the 500-Hz f_0 DL appeared to be larger than the 1500-Hz pure-tone frequency difference limen (FDL) in a pilot run, suggesting that the f_0 DL had not reached its asymptotic value. For NH listeners, nine f_0's (75–500 Hz) were tested in the random-phase conditions. The 500-Hz f_0 was not tested for the sine-phase conditions, resulting in a total of eight f_0's tested in these listeners.

2. Stimulus level

It was desirable to keep both the sensation level (SL) and overall sound pressure level (SPL) similar for all listeners so as to control for the known influences of these two factors on f_0 discrimination performance (respectively, Hoekstra, 1979; Bernstein and Oxenham, 2006). Therefore, all stimuli were presented in a background of threshold equalizing noise (TEN; Moore *et al.*, 2000), which is intended to yield pure-tone detection thresholds in noise that are approximately constant across frequency. Presented in a TEN background, pure tones presented at equal SPL will also have roughly equal SL. For each HI listener, the TEN was set to a level that, in a NH listener, would yield tone-in-noise detection thresholds at least as high as the HI listener's detection thresholds in quiet. Initially, the TEN level was intended to be the same for all listeners. Tone-in-quiet thresholds, estimated using a three-interval three-alternative forced-choice, two-down, one-up adaptive procedure, were no higher than 50 dB SPL in the 1.5–3.5 kHz range for each of the first five HI listeners recruited for the study. For these listeners, the level of the background noise was set to 50 dB SPL per ERB_N, where ERB_N is the equivalent rectangular bandwidth of auditory filters in NH listeners as described by Glasberg and Moore (1990). After measurements had been made for the initial five listeners, five additional listeners (six ears) were recruited for the study. Three of these six additional ears had at least one tone-in-quiet threshold in the 1.5–3.5 kHz range above 50 dB SPL. For these ears, the TEN level (Table I, column 7) was set to 60 dB SPL (two ears) or 62 dB SPL (one ear) depending on the maximum absolute threshold measured in the 1.5–3.5 kHz range (Table I, column 6).

To set stimulus levels, detection thresholds were measured for pure tones in the TEN background. The 0 dB SL reference was determined for each listener individually, and was taken as the mean of six threshold measurements, two estimates each for pure-tone frequencies of 1.5, 2, and 3 kHz. Across the HI listeners, the 0 dB SL reference ranged from −2.9 to +3.5 dB *re* the TEN level in dB SPL/ERB_N.

Because of the different levels tested for the HI listeners, NH listeners were tested with both 50 dB SPL/ERB_N and 65 dB SPL/ERB_N TEN, to ensure that stimuli were presented at a level at least as high as the highest level presented to HI listeners. Due to a lack of testing time, sine-phase conditions were not tested at the higher level in NH listeners. Across the NH listeners, the 0 dB SL reference ranged from −3.8 to −1.8 dB and from −3.1 to −1.0 dB *re* the 50 and 65 dB SPL/ERB_N TEN levels, respectively.

Stimuli were presented at a nominal 12.5 dB SL per component in a TEN background at the levels specified in Table I. Exceptions to the procedure for setting the stimulus level were made for three listeners (two NH, one HI) where the stimuli presented in 62–65 dB SPL/ERB_N noise were uncomfortably loud at the 75- and/or 125-Hz f_0. For the listeners and conditions where this occurred, stimulus levels were reduced somewhat, or the conditions were eliminated.[3] To prevent contralateral detection of the stimuli, uncorrelated TEN was presented to the nontest ear at 20 dB below the level of that presented to the test ear.

3. Procedure

Five f_0 DL measurements were made for each combination of f_0, phase, and stimulus level. For each listener, all of the random-phase conditions were tested before the sine-phase conditions because the decision to include sine-phase measurements was not made until the random-phase data had already been collected for the first five HI listeners. FDLs for a 1500-Hz pure tone were measured as an additional condition interspersed with the f_0 DL estimates for harmonic complexes. Five FDL measurements each were interspersed with the measurements involving random- and sine-phase stimuli. The f_0 and stimulus level conditions were presented in random order.

Fundamental frequency DLs and FDLs were estimated in a three-interval three-alternative forced-choice (3I-3AFC) adaptive procedure, using a two-down, one-up algorithm to track the 70.7% correct point on the psychometric function (Levitt, 1971). Two intervals contained a stimulus with a reference f_0 ($f_{0,\mathrm{ref}}$) and the other interval contained a complex with a higher f_0. The listener's task was to identify the interval containing the complex with the higher pitch. The f_0 difference (Δf_0) was initially set to 20% of the f_0, changed by a factor of 1.59 until the second reversal, and then changed by a factor of 1.26 for six more reversals. The f_0 DL was estimated as the geometric mean of the Δf_0's at the last six reversal points.

To reduce the potential effectiveness of loudness as an alternative cue, the root-mean-squared (rms) power was first equalized across the three intervals by increasing the stimulus level per component for the interval containing the higher f_0, and then a random level perturbation was added to each interval, chosen from a uniform distribution of ±2.5 dB. In addition, $f_{0,\mathrm{ref}}$ was roved from trial to trial within a run, chosen from a uniform distribution between ±5% of the average f_0. This was intended to encourage listeners to compare the pitches of the stimuli across each of the intervals of one trial, rather than comparing the pitch in each interval with some internally stored representation of the $f_{0,\mathrm{ref}}$, although the f_0 roving may not have been effective for low f_0's where the measured f_0 DLs were relatively large.

4. Apparatus

The stimuli were generated digitally and played out via a soundcard (LynxStudio LynxOne) with 24 bit resolution and a sampling frequency of 32 kHz. The stimuli were then passed through a programmable attenuator (TDT PA4) and headphone buffer (TDT HB6) before being presented to the listener via one earpiece of a Sennheiser HD 580 headset. Listeners were seated in a double-walled sound-attenuating chamber. Intervals were marked by colored boxes on a computer screen, and visual feedback (correct/incorrect) was provided following each response.

D. Results

Figure 2 plots f_0 DLs as a function of f_0 for six sample HI listeners [I5, I6, I7, I9(l), I9(r), and I10], representing the range of results observed across the 11 HI ears, and the mean f_0 DLs across the three NH listeners at each of the two stimulus levels. Each of the five HI listeners for whom data are not shown yielded very similar results to other subjects shown in Fig. 2. Results for listeners I2, I3, and I4 were, like I6 and I10, very similar to those for the NH listeners, while listeners I1 and I8 showed more abnormal results, comparable to those for I7 and I9(r). "Low" and "high" levels for NH listeners refer to stimuli presented in 50 and 65 dB SPL/$\mathrm{ERB_N}$ background TEN, respectively. Random-phase conditions are denoted by circles and sine-phase conditions by squares. The solid lines in Fig. 2 represent fitted functions to the random-phase data, and the dashed vertical lines represent midpoints of the transitions in the functions, as described in Sec. V A.

Four main findings are apparent in the results. First, for most listeners and phase conditions, f_0 DLs generally transitioned from large to small with increasing f_0. This is consistent with previous results in NH listeners (Hoekstra, 1979; Shackleton and Carlyon, 1994; Bernstein and Oxenham, 2005; 2006) and is thought to reflect the transition from all unresolved to some resolved harmonics, although Moore *et al.* (2006) have interpreted this result as reflecting a progressive decline in the ability to use temporal fine-structure information (see Sec. VI B). Second, the f_0 where the f_0 DL transition occurred (the f_0 transition point, $f_{0,tr}$), varied across listeners. NH listeners and listeners with relatively mild hearing loss (e.g., I6 and I10) showed the transition at a relatively low f_0 of around 200 Hz, whereas listeners with more severe hearing loss [e.g., I7 and I9(r)] tended to have transitions at higher f_0's of 500 Hz or more. The hypothesis that the across-listener variability in the f_0 DL transition point is related to frequency selectivity is examined quantitatively in Sec. V. Third, the results from some HI listeners show substantial nonmonotonicities in the pattern of results [e.g., I5, I7, and I9(r)]. For these listeners, f_0 DLs are elevated at moderate f_0's, which may result from unresolved

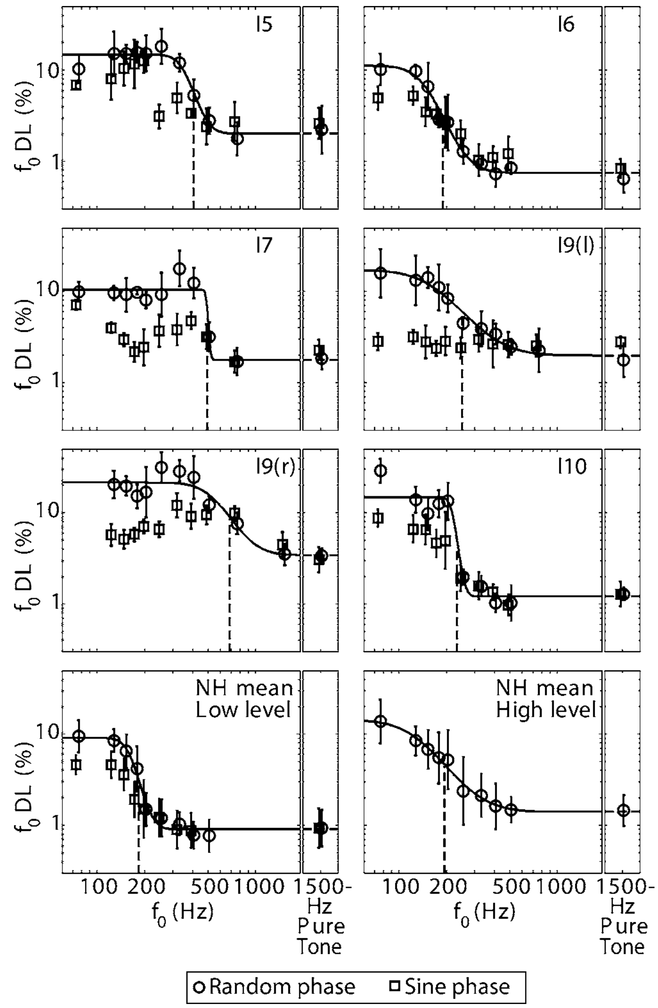

FIG. 2. (Top six panels) f_0 DLs plotted as a function of f_0, and FDLs for a 1500 Hz pure-tone FDL, for six example HI listeners. (Bottom two panels) mean f_0 DLs and FDLs across the three NH listeners at two stimulus levels. Error bars indicate the standard deviation of the five f_0 DL or FDL measurements for each HI listener, and the standard deviation across the three mean f_0 DLs or FDLs for NH listeners. Dashed curves indicate the sigmoid functions that best fit the random-phase data, for each individual HI listener or the mean NH data (see Sec. V A). Vertical dashed lines indicate the $f_{0,\mathrm{tr}}$, defined as the f_0 that yielded random-phase f_0 DLs halfway (on a log scale) between maximum and minimum.

harmonics that yield an envelope repetition rate too high to be processed efficiently (e.g., Kohlrausch *et al.*, 2000). Overall, flat or nonmonotonic f_0 DL functions were observed for three and five HI listeners (out of 11) in the random- and sine-phase conditions, respectively. Fourth, for most listeners, the phase relationships between harmonics affected f_0 DLs for low f_0's, but not high f_0's, consistent with previous results in NH hearing listeners (Houtsma and Smurzynski, 1990; Bernstein and Oxenham, 2003) and with the idea that complexes with high f_0's contain mostly resolved harmonics. This result provided an additional estimate of harmonic resolvability (see Sec. V A 3) based on the range of stimulus f_0's for which there was an f_0 DL phase effect.

III. EXPERIMENT 2: MODULATION DISCRIMINATION

A. Rationale

Frequency selectivity was estimated by measuring listeners' ability to discriminate between sinusoidal amplitude modulation (SAM) and quasi-frequency modulation (QFM; Zwicker, 1952). The two sounds were three-tone complexes with identical amplitude spectra but different relative phases between components. Previous results have shown that HI listeners can perform this task out to higher modulation frequencies than can NH listeners (Nelson and Schroder, 1995), and that performance improves at high stimulus levels for NH listeners (Nelson, 1994). This is thought to be because the wider peripheral filters associated with SNHL (or high stimulus levels in NH listeners) increase the likelihood of peripheral interactions between components. The hypothesis that small f_0 DLs require resolved harmonics suggests that *better* SAM/QFM discrimination (i.e., a higher maximum modulation frequency) should correlate with *poorer* f_0 discrimination performance (i.e., a higher $f_{0,\mathrm{tr}}$). One advantage of testing this prediction is that HI listeners should perform better than NH listeners, such that the interpretation of the results should not be confounded by any nonspecific perceptual or cognitive deficits for the HI listeners (who were, on the average, older than the NH listeners). Also, this experiment estimates frequency selectivity by varying the spacing between adjacent frequency components, a situation analogous to that of the f_0 DL measures in Experiment 1.

B. Methods

As in the studies of Nelson (1994) and Nelson and Schroder (1995), the current experiment measured discrimination between SAM and QFM complexes as a function of the modulation frequency (f_m). The carrier frequency (f_c) was fixed at 1500 Hz (the lower cutoff frequency of the bandpass filter used in Experiment 1). In this three-interval three-alternative forced-choice task, two intervals contained SAM complexes and the third contained a QFM complex. Listeners were asked to identify the interval containing the stimulus that was different from the other two. Visual feedback (correct/incorrect) was provided. Each interval consisted of a three-component tone complex, with frequencies $f_c - f_m$, f_c, and $f_c + f_m$, and duration 500 ms (including 30 ms raised cosine onset and offset ramps). The intervals were separated by silent gaps of 375 ms.

The wideband background TEN was not used in this experiment because it was found to be too distracting and detrimental to performance in the modulation discrimination task. Instead, a low-pass TEN with a cutoff frequency of ($f_c - 1.95 f_m$) was used to mask any distortion products occurring at frequencies of $f_c - 2f_m$ or below. The low-pass TEN had the same spectral characteristics as the wideband TEN of Experiment 1 for frequencies below its cutoff. The low-pass TEN was turned on 250 ms before the first interval and turned off 250 ms following the offset of the third interval, for a total duration of 2750 ms.

Although the wideband TEN was not used, the level of the center component was set at a SPL equal to the 12.5 dB SL level that was used in Experiment 1, adjusted for each listener. The level of each sideband was 6 dB below that of the center component, producing 100% amplitude modulation in the SAM case. The SAM complexes were generated by setting the three components to be in sine starting phase. The QFM complexes were identical to the SAM complexes except that the starting phase of the center component was advanced by 90°.

The f_m's were set to the f_0 values tested in the sine-phase conditions of Experiment 1 (eight f_m's for NH listeners, nine or ten f_m's for HI listeners). Each run included four trials for each f_m, presented in random order. Each HI listener completed 13 runs for a total of 52 stimulus presentations for each f_m, with two exceptions, detailed below. Each NH listener was tested with the stimulus level set relative to the detection threshold in both the 50 and 65 dB SPL/ERB$_\mathrm{N}$ TEN, with 13 runs presented at each level. The same 11 HI and 3 NH listeners from Experiment 1 participated in this experiment. Each listener completed at least 1 h of practice before the measurement period began.

Two HI listeners (I6 and I8) were unable to achieve much above chance performance even for the lowest f_m tested of 75 Hz, unless the randomization of f_m within a run was greatly diminished. For these two listeners, eight trials each of two f_m's were presented within a run. Seven runs were completed for each pair of f_m's for a total of 56 stimulus trials per f_m. With this modification, one of the listeners (I6) still failed to achieve 100% correct for the 75 Hz f_m. Two additional f_m's (25 and 50 Hz) were added for this listener, who achieved near-perfect performance at both f_m's.

C. Results

The upper six panels of Fig. 3 show the percent correct as a function of f_m for the same six sample HI listeners whose f_0 DLs were shown in Fig. 2. Again, the performance of the listeners not shown was generally within the range of those shown in the graphs. The lower two panels of Fig. 3 show the percent correct for each of the three NH listeners for each f_m at the low and high stimulus levels. Each listener showed qualitatively similar results, with performance decreasing from near 100% correct for the lowest f_m tested to near chance (33%) for the highest f_m tested. The solid lines represent sigmoidal fits, and the vertical dashed lines represent estimates of the 66.7% correct point based on the fitted functions, as described in Sec. V A 4. No consistent nonmonotonicities were observed in the results, suggesting that the nonmonotonicities observed by Nelson and Schroder (1995) may have derived from combination tones that were masked by the low-pass noise in the current experiment. The data shown in Fig. 3 generally support the hypothesis that listeners with poorer frequency selectivity can perform better than normal (i.e., out to a higher modulation frequency) in the modulation discrimination task. NH listeners and HI listeners with mild hearing loss (e.g., I6 and I10) who performed best at f_0 discrimination (Fig. 2) performed worst at discriminating QFM from SAM (Fig. 3). Conversely, listeners with more moderate-to-severe hearing loss who were poor discriminators of f_0 performed best at discriminating QFM from SAM at high modulation frequencies [e.g., I5, I7, I9(l), and I9(r)]. However, this was not always the case. For example, I8 had a relatively high $f_{0,\mathrm{tr}}$ but still showed difficulty in performing this task. The relationship between performance in this task and the f_0 DLs measured in Experiment 1 is evaluated in more detail for all listeners in Sec. V.

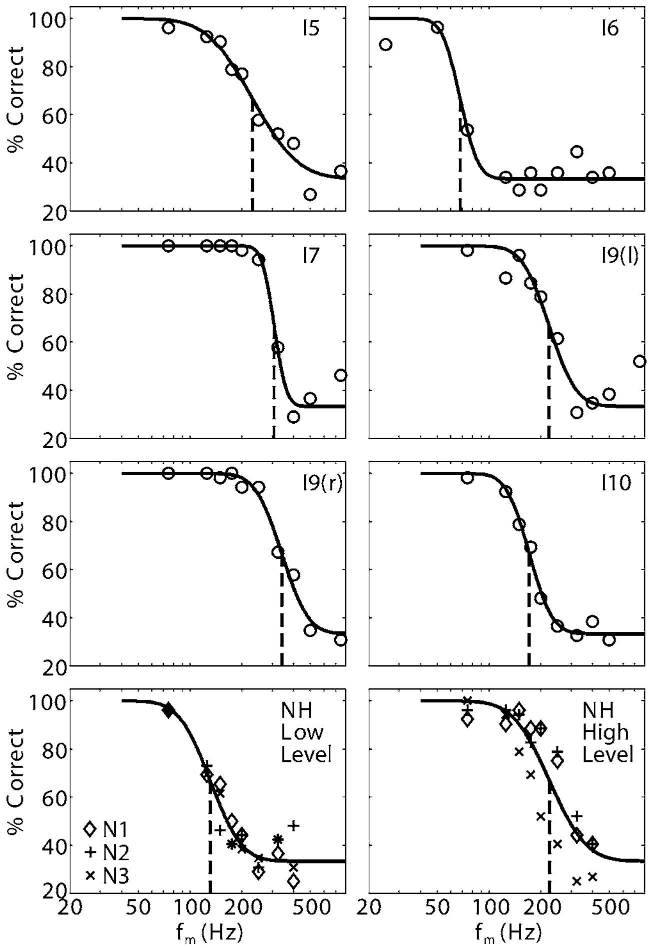

FIG. 3. Results of Experiment 2, showing the percentage correct in discriminating between SAM and QFM as a function of f_m, the frequency spacing between components, for the six sample HI listeners of Fig. 2 (top six panels), and for the three NH listeners at the two stimulus level (two lower panels). Dashed curves indicate the sigmoid function that best fit the data for each HI listener or for the pooled NH data at each level. Vertical dashed lines indicate the estimate of the threshold f_m ($f_{m,\mathrm{tr}}$) yielding 67% correct performance, halfway between perfect performance (100%) and guessing (33%).

IV. EXPERIMENT 3: AUDITORY FILTER SHAPES

A. Rationale

The current standard for evaluating peripheral frequency selectivity in the spectral domain is the notched-noise method of auditory filter-shape estimation (Patterson, 1976). This experiment used a "fixed signal level" version of the notched-noise method described by Rosen and Baker (1994) to estimate auditory filter bandwidths in the NH and HI listeners who participated in Experiments 1 and 2. The level of the notched-noise masker that just masked a pure tone was measured as a function of the masker's spectral notch width. At threshold, this paradigm is thought to deliver roughly constant overall (signal plus noise) power across notch widths at the output of auditory filter in question, thus reducing the possible confounding influence of variations in filter shape with input level.

B. Methods

Throughout the experiment, the pure-tone signal had a constant frequency (f_{sig}) of 1500 Hz, corresponding to the low-frequency edge of the passband in Experiment 1. The signal was fixed at the SPL level corresponding to 10 dB SL (adjusted for each listener individually) ***re*** the TEN level that was used in Experiment 1. Although the signal SPL was adjusted relative to the detection threshold in TEN, the TEN background was not used. The NH listeners were only tested with the signal at one level (10 dB *re* the detection threshold in 50 dB SPL/ERB$_N$ TEN) because a signal at the higher level could not be comfortably masked for wide notch widths in these listeners.

Each trial in the experiment consisted of three intervals, each with a 700-ms duration, separated by 500-ms silent gaps. Two of the intervals contained only a 700 ms noise burst (including 10-ms raised-cosine onset and offset ramps). The other interval also contained a 500-ms pure-tone signal (including 30-ms raised-cosine onset and offset ramps), temporally centered within the noise burst. The listeners' task was to identify which of the three intervals contained the pure-tone signal. A 3I-3AFC procedure with a two-up, one-down adaptive algorithm tracked the 70.7% correct point (Levitt, 1971). The spectrum level of the noise (dB SPL/Hz) was initially set to −35 dB *re* the TEN noise level (dB SPL/ERB$_N$) for each listener, and changed by 8 dB for the first two reversals, 4 dB for the next two reversals, and 2 dB for the last eight reversals. Threshold was estimated as the mean of the noise levels at the last eight reversal points. Reported thresholds are the means of three such threshold estimates.

The noise masker consisted of two bandpass noises, each with a bandwidth of 200 Hz. The notch width was defined in terms of the deviations from the signal fre quency, expressed as a proportion of f_{sig}, of both the high-frequency edge of the lower-frequency noise band (Δf_l) and the low-frequency edge of the upper-frequency noise band (Δf_u). Five symmetrical notch conditions were presented, with equal Δf_l and Δf_u values of 0, 0.1, 0.2, 0.3, and 0.4f_{sig}. To allow for the possibility of asymmetrical filters, there were also four asymmetric conditions $[(\Delta f_l, \Delta f_u) = (0.1f_{\mathrm{sig}}, 0.3f_{\mathrm{sig}}), (0.2f_{\mathrm{sig}}, 0.4f_{\mathrm{sig}}), (0.3f_{\mathrm{sig}}, 0.1_{\mathrm{sig}})$, and $(0.4f_{\mathrm{sig}}, 0.2f_{\mathrm{sig}})]$. A low-pass noise was included to mask any possible low-frequency combination bands (Greenwood, 1972) that could facilitate the detection of the signal, with a cutoff frequency equal to the low-frequency edge of the lower-frequency noise band and a spectrum level 20 dB below that of the notched noise.

C. Analysis

A standard fitting procedure was used to derive auditory filter shapes from the data (Glasberg and Moore, 1990). The fitting procedure took into account the Sennheiser H580 transfer function, the middle-ear transfer function, the possibility of off-frequency listening, and variations in filter bandwidth with center frequency (CF), as described by Glasberg and Moore (1990). Four different filter-shape models were tested, based on all permutations of symmetrical or asymmetrical filter tips (same or different upper- and lower-frequency slopes, p_l and p_u) and the presence or absence of a dynamic range limit (r) on the lower-frequency slope. The

TABLE II. The accuracy of four auditory filter models in fitting the notched-noise masking data across 14 NH and HI listeners.

Filter tip	Dynamic range limitation?	Free parameters	rms fitting error (dB)
Symmetric	Yes	3	1.24
Asymmetric	Yes	4	1.14
Symmetric	No	2	1.42
Asymmetric	No	3	1.31

dynamic range limit was never applied to the upper-frequency slope, thus simulating the uniformly steep upper slope often found in auditory-nerve and basilar-membrane tuning curves (e.g. Kiang *et al.*, 1965; Sellick *et al.*, 1982). The signal-to-noise ratio at the output of a model filter required for signal detection provided an additional free parameter in all four models. All four filter models yielded similar rms fitting errors (Table II), although there was a small advantage for filter models incorporating a larger number of free parameters. Bernstein and Oxenham (2006) found that variation in the $f_{0,\mathrm{tr}}$ across stimulus level in NH listeners was well accounted for by variation in the dynamic range limitation across level in the auditory filter model used to fit the notched-noise masking data. Therefore, in the current study, a filter model with a dynamic range limitation was chosen to characterize frequency selectivity for the regression analyses described in Sec. V. Because the rms error was only marginally improved by the addition of a fourth free parameter in the asymmetrical case, the filter model with a symmetrical tip was selected. The asymmetrical application of the dynamic-range limitation and the combination of off-frequency listening and proportional variation in filter bandwidth with CF accounted reasonably well for unequal threshold measurements in the four asymmetric notch conditions (overall rms fitting error 1.16 dB vs 1.31 dB for the symmetric conditions). The equivalent rectangular bandwidths (ERBs) of the filters were derived from the fitted parameters.

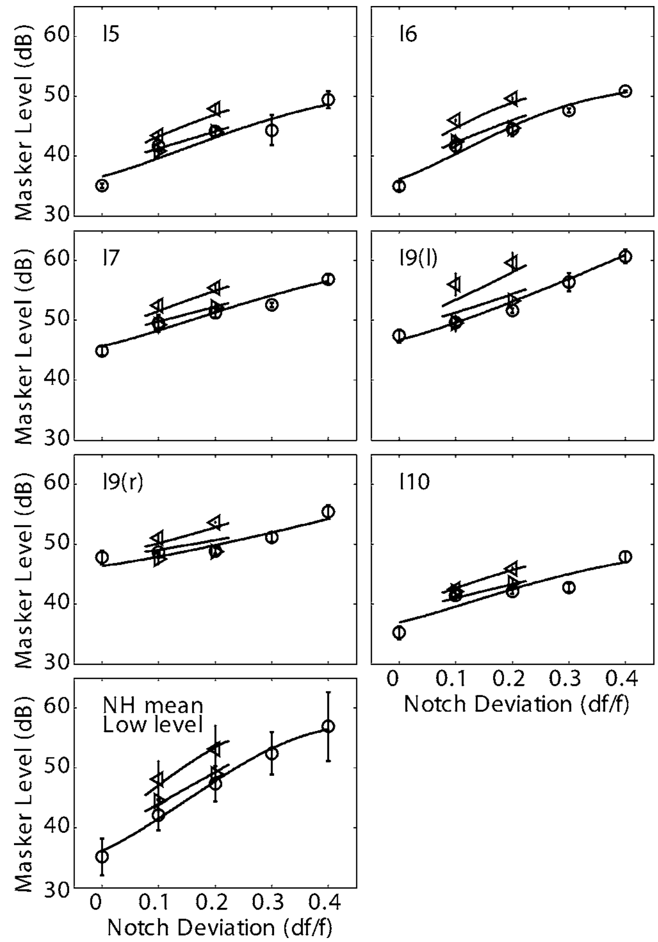

FIG. 4. The notched-noise masking level needed to just mask a 1500 Hz probe tone presented at 10 dB re the threshold in TEN at the level indicated in Table I. Circles indicate notches that are symmetrical around the probe-tone frequency. Left- and right-pointing triangles indicate asymmetrical notches, shifted toward lower and higher frequencies, respectively. For the asymmetrical conditions, data are plotted according to the notch edge closest to the probe frequency, and the second notch edge was $0.2/f_{\mathrm{sig}}$ farther away from the probe frequency. Solid lines indicate the predicted masker levels based on the best fitting auditory filter shape. Error bars indicate the standard deviation across the three masking measurements for the HI listeners, or across the three NH listeners.

D. Results

Figure 4 shows the notched-noise masking data along with the masking predictions based on the best-fitting filter functions (solid lines) for each of the six example HI listeners (upper six panels) from Figs. 2 and 3, and for the mean of the three NH listeners (lower panel). As in Figs. 2 and 3, the performance of the listeners not shown was generally within the range of those shown in the graphs. Circles represent conditions with symmetrical noise notches, while left- and right-pointing triangles represent asymmetrical conditions where Δf_l was greater than and less than Δf_u, respectively. The simple filter-shape model yielded a reasonable fit to the data for each listener. As expected, HI listeners generally showed broader frequency selectivity than did NH listeners. This can be seen in Fig. 4 by the generally shallower increase in masker level as a function of notch width in the HI than in the NH listeners. Although for illustrative purposes fits are shown for the mean NH data in the lower panel of Fig. 4, fits were performed for each individual NH listener for the across-listener analyses described in the following section.

V. ANALYSIS

A. Summary measures

Each of the experiments described above yielded summary values that were then used to derive correlations between the measures of f_0 discrimination (Experiment 1) and the measures of frequency selectivity (Experiments 1, 2, and 3). The different summary measures, and the way they are derived, are described below. The values for each of these measures for each listener are shown in Table III, with boldface entries indicating HI values that fell more than two standard deviations above the mean NH values (or above or below the mean NH values in the case of the f_0 DL slope, see Sec. V A 2) at a comparable stimulus level.[4] Although the experimental design was intended to investigate correlations

TABLE III. Best-fit estimates for individual listeners of four aspects of the f_0 DL data and three frequency selectivity estimates. Logarithmic transformations of the data shown here [except for m which is already in the logarithmic domain in Eq. (1)] were used in the correlation analyses of Figs. 6–8 and Table IV. Boldface entries indicate values for HI listeners that fell more than two standard deviations (of the NH values) above the mean NH values at a comparable level (or more than two standard deviations above *or* below the mean NH values in the case of m). Asterisks (*) indicate cases where the high-level HI values were compared to low-level NH mean values because no NH data were available at the high level.

		f_0 discrimination				Frequency selectivity		
	Listener	$f_{0,\mathrm{tr}}$ (Hz)	f_0 $\mathrm{DL}_{\mathrm{min}}$ (%)	f_0 $\mathrm{DL}_{\mathrm{max}}$ (%)	Slope (m)	$f_{0,\mathrm{PE}}$ (Hz)	$f_{m,\mathrm{tr}}$ (Hz)	ERB (Hz)
Hearing impaired	I1	182.7	**1.84**	**32.86**	**1.70**	**275.7**	**287.7**	395.6
	I2	**214.9**	**1.44**	13.93	7.92	**246.2**	**143.3**	**406.2**
	I3	187.3	1.29	**21.61**	5.51	154.4	**166.0**	**482.0**
	I4	**203.5**	**1.38**	**25.31**	**3.46**	167.2	**153.2**	**517.2**
	I5	**403.2**	**2.02**	14.84	8.68	**489.0**	**230.7**	**543.1**
	I6	189.6	0.75	11.16	5.06	165.3	68.0	**409.4**
	I7	**493.6**	1.76	10.42	**54.53**	**446.9***	308.4	**618.7***
	I8	**345.1**	**3.60**	**23.86**	7.73	**330.9**	**152.0**	**454.0**
	I9(I)	250.5	**1.99**	17.17	3.11	**259.8***	223.9	**564.7***
	I9(r)	**687.4**	**3.45**	21.42	4.85	**462.7***	**341.0**	**941.5***
	I10	**231.9**	1.21	14.91	18.61	**241.1**	**171.6**	**623.0**
Normal hearing low level	N1	192.2	0.66	5.87	14.13	186.2	128.5	343.8
	N2	173.8	0.96	9.82	13.83	175.4	136.8	347.7
	N3	184.1	1.10	11.68	7.55	204.7	131.4	282.5
	Mean	183.4	0.91	9.12	11.84	188.8	132.2	324.7
	St. Dev.	9.2	0.22	2.97	3.72	14.8	4.2	36.6
Normal hearing high level	N1	196.4	1.06	5.79	14.52		269.4	
	N2	246.5	1.59	13.40	3.03		260.0	
	N3	160.8	1.48	31.40	2.62		174.5	
	Mean	201.2	1.38	16.86	6.72		234.6	
	St. Dev.	43.1	0.28	13.15	6.76		52.3	

between f_0 discrimination and frequency selectivity measures rather than to compare groups of impaired and normal listeners, this information is provided to demonstrate that many impaired listeners showed quantitatively abnormal results.

Four measures of f_0 discrimination performance were derived from the random-phase f_0 DL data. A sigmoid function[5] was fit to the log-transformed f_0 DL vs. log-transformed f_0 data (Fig. 2). A fit was made to the data for each HI listener and separately to the data at each of the two stimulus levels for each NH listener. The fitting procedure adjusted four free parameters, representing estimates of (1) the maximum ($f_0\,\mathrm{DL}_{\mathrm{max}}$) and (2) the minimum f_0 DL ($f_0\,\mathrm{DL}_{\mathrm{min}}$) attained at very low and very high f_0's, respectively, (3) the f_0 at which f_0 DLs transitioned from large to small ($f_{0,\mathrm{tr}}$), and (4) the slope (m) of the transition. The FDL data measured for the 1500 Hz pure tone were included in the fitting procedure, with f_0 set to infinity, because a pure tone can be thought of as "infinitely" resolved.[6] With the f_0 set to infinity, the FDL data should only directly influence the estimate of the parameter $f_0\,\mathrm{DL}_{\mathrm{min}}$, since changes in $f_{0,\mathrm{tr}}$, $f_0\,\mathrm{DL}_{\mathrm{max}}$ and m do not affect the value of the sigmoid function at an f_0 of infinity. Because the nonmonotonicities observed in the sine-phase f_0 DL data prohibited a satisfactory fit for some listeners, only the random-phase data were analyzed in this way. The sigmoid functions that best fit the random-phase data are shown as solid curves in Fig. 2. While fitted curves are shown for the mean NH data in the lower two panels in Fig. 2, fits were made for each individual NH listener for the regression analyses described in Sec. V B, below.

1. The f_0 DL transition point ($f_{0,tr}$)

The $f_{0,\mathrm{tr}}$, one of the parameters in the sigmoid fitting procedure, provides an estimate of the f_0 for which DLs were halfway (on a log scale) between maximum and minimum. Seven out of 11 HI ears had an $f_{0,\mathrm{tr}}$ more than two standard deviations above the NH mean at a comparable level (boldfaced entries in Table III).

2. Maximum and minimum f_0 DL values ($f_0\,\mathrm{DL}_{\mathrm{max}}$ and $f_0\,\mathrm{DL}_{\mathrm{min}}$) and the f_0 DL slope (m)

These values were also derived from the sigmoidal fits to data in Experiment 1. The values of $f_0\,\mathrm{DL}_{\mathrm{max}}$ and $f_0\,\mathrm{DL}_{\mathrm{min}}$ provide estimates of the f_0 discrimination performance associated with completely unresolved and resolved harmonics, respectively. The value of m provides an estimate of the rate at which the f_0 DL transitioned from its maximum to minimum value. These three summary measures did not form part of the original hypothesis regarding pitch discrimination and frequency selectivity, but certain relationships were found between $f_0\,\mathrm{DL}_{\mathrm{min}}$ and the other measures, which are described in the correlational analyses below. The $f_0\,\mathrm{DL}_{\mathrm{min}}$ was more than two standard deviations above the NH mean at a comparable level for seven out of the 11 impaired ears (boldfaced entries in Table III). The elevated $f_0\,\mathrm{DL}_{\mathrm{min}}$ in HI lis-

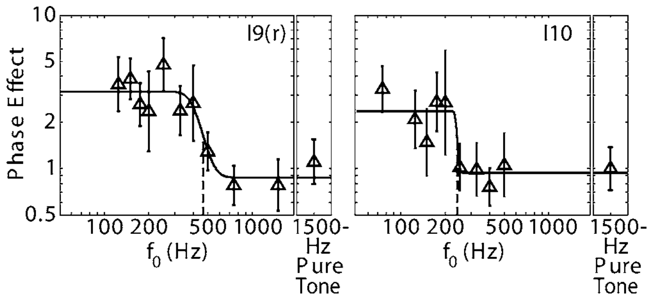

FIG. 5. The f_0 DL phase effect (PE), defined as the ratio between random- and sine-phase f_0 DLs, for two sample HI listeners. The ratio between pure-tone FDLs for trials that were interspersed with the sine- and random-phase f_0 DL conditions were also calculated to demonstrate any possible learning effects (right column of each panel). Error bars indicate the standard deviation across the 25 PE estimates for each HI listener. Solid curves indicate the sigmoid functions that best fit the PE data. Vertical dashed lines indicate the phase-effect transition f_0 ($f_{0,\mathrm{PE}}$) defined as the f_0 for which the phase effect was halfway (on a log scale) between maximal and minimal.

teners suggests that the frequencies of individual resolved harmonics are more poorly encoded, consistent with previous studies of pure-tone frequency discrimination in listeners with SNHL (e.g., Tyler *et al.*, 1983; Moore and Glasberg, 1986; Moore and Peters, 1992). The effects of hearing loss on f_0 $\mathrm{DL}_{\mathrm{max}}$ and m were less clear. Estimates of f_0 $\mathrm{DL}_{\mathrm{max}}$ were more than two standard deviations above the NH mean for only four HI ears (boldfaced entries in Table III). Estimates of m were more than two standard deviations above or below the NH mean for one and two HI ears, respectively.

3. The phase-effect transition point ($f_{0,PE}$)

The phase-effect transition point ($f_{0,\mathrm{PE}}$) is also derived from Experiment 1 (Fig. 2), but relates to the effect of phase on f_0 DLs, providing an estimate of harmonic resolvability based on the idea that the relative phase between successive components should only affect f_0 DLs if the components are unresolved and interact within individual auditory filters. In all listeners, f_0 DLs were larger in the random- than the sine-phase conditions for low but not for high f_0's, consistent with the idea that only complexes with high f_0's contain resolved harmonics. This observation was confirmed by two-factor (f_0 and phase) ANOVAS performed on the f_0 DL data for each individual listener, with all listeners showing a significant ($p<0.05$) interaction between f_0 and phase.

The f_0 DL phase effect (PE) was defined as the ratio between the f_0 DLs measured in random- and sine-phase conditions. Resampling was performed to obtain all possible estimates of the PE by recalculating the PE 25 times for each f_0, once for each combination of the five repeated f_0 DL measurements made for each phase relationship. The mean and standard deviations of the 25 PE estimates for each f_0 (and for the 1500 Hz pure tone) are plotted in Fig. 5 for two sample HI listeners that illustrate the range of observed responses. Because the random-phase conditions were always tested before the sine-phase conditions, general differences between the random- and sine-phase conditions might be attributable to learning effects. To control for this possibility, "phase-effect" ratios were also calculated for the 1500 Hz pure-tone FDL measurements that were interspersed in each f_0 DL phase condition.

For all listeners, the PE was generally greater than one for low f_0's (f_0 DLs affected by component phase), and approximately equal to one for high f_0's (no phase effect), although the maximum f_0 for which a PE was observed varied across listeners. To estimate the transition f_0 at which phase no longer affected f_0 DLs for each listener, a sigmoid function with four free parameters was fit to the log transforms of the 25 PE estimates at each f_0 (solid curves in Fig. 5).[7] As with the fits to the random-phase f_0 DL data, the PE estimates for the 1500 Hz pure tone were included in the fitting procedure, with f_0 set to infinity. This was done instead of setting the value of the sigmoid function to zero for infinite f_0's to allow some flexibility in the value of the PE function at high f_0's depending on the variance in the pure-tone FDLs. The PE transition f_0 ($f_{0,\mathrm{PE}}$) was defined as the f_0 for which the PE was halfway between its maximum and minimum log-transformed values (vertical dashed lines in Fig. 5). By characterizing the transition point of the PE function, any overall improvement due to learning effects in the sine-phase relative to the random-phase conditions would be factored out. Eight out of 11 HI ears had $f_{0,\mathrm{PE}}$'s more than two standard deviations above the NH low-level mean (boldfaced entries in Table III).

4. Modulation discrimination transition point

The modulation frequency at which QFM and SAM became indistinguishable (Experiment 2) provided another estimate of component resolvability, based on the idea that QFM and SAM should only be discriminable if the stimulus components are unresolved. A sigmoid function fixed at 100% and 33% correct at the extremes was fit (minimum least squares) to the percentage correct data as a function of the log-transformed f_m's (solid curves in Fig. 3). The 67% correct point of this function was taken as the estimate of the transition f_m ($f_{m,\mathrm{tr}}$) between resolved and unresolved components (vertical dashed lines in Fig. 3). The $f_{m,\mathrm{tr}}$ was more than two standard deviations above the NH mean at a comparable level for eight out of the 11 HI ears (boldfaced entries in Table III), supporting the hypothesis that HI listeners with wider peripheral filters should perform better than NH listeners in this task.

5. Equivalent rectangular bandwidth (ERB)

The ERB of the filter shape that best fit the notched-noise masking data (Experiment 3) provided a third estimate of frequency selectivity. ERBs were more than two standard deviations above the NH low-level mean for ten out of the 11 HI ears (boldfaced entries in Table III).

B. Regression analyses

Table IV lists the results of single regression analyses performed between each of the four measures of f_0 discrimination ($f_{0,\mathrm{tr}}$, f_0 $\mathrm{DL}_{\mathrm{min}}$, f_0 $\mathrm{DL}_{\mathrm{max}}$, and m), each of the three estimates of frequency selectivity ($f_{0,\mathrm{PE}}$, $f_{m,\mathrm{tr}}$, and ERB) and the degree of hearing loss at 1.5 kHz ($\mathrm{HL}_{1.5\mathrm{k}}$). Squared Pear-

TABLE IV. Squared Pearson correlation coefficients (R^2) for bivariate correlations between f_0 DL and frequency selectivity measures. Boldface entries indicate significant ($p<0.05$) correlations. Asterisks (*) indicate that partial correlations were significant when controlling for TEN level ($p<0.05$, partial R^2 values not shown). "N/A" indicates that 17 data points were not available because NH listeners were tested at only one level for at least one of the measures associated with a given cell.

Data included in analysis	Measure	$f_{0,\mathrm{tr}}$	f_0 $\mathrm{DL}_{\mathrm{min}}$	f_0 $\mathrm{DL}_{\mathrm{max}}$	m	$f_{0,\mathrm{PE}}$	$f_{m,\mathrm{tr}}$	ERB
All listeners N=14	$\mathrm{HL}_{1.5\mathrm{k}}$	**0.50**	$\mathbf{0.52}^{*}$	$\mathbf{0.38}^{*}$	0.02	$\mathbf{0.51}^{*}$	$\mathbf{0.52}^{*}$	$\mathbf{0.68}^{*}$
	$f_{0,\mathrm{tr}}$		$\mathbf{0.54}^{*}$	0.02	0.13	$\mathbf{0.80}^{*}$	**0.44**	**0.62**
	f_0 $\mathrm{DL}_{\mathrm{min}}$			$\mathbf{0.45}^{*}$	0.00	$\mathbf{0.57}^{*}$	$\mathbf{0.48}^{*}$	**0.38**
	f_0 $\mathrm{DL}_{\mathrm{max}}$				0.20	0.04	0.17	0.14
	m					0.13	0.08	0.04
	$f_{0,\mathrm{PE}}$						$\mathbf{0.56}^{*}$	**0.37**
	$f_{m,\mathrm{tr}}$							**0.41**
HI listeners only N=11	$\mathrm{HL}_{1.5\mathrm{k}}$	**0.58**	0.34	0.01	0.13	$\mathbf{0.64}^{*}$	$\mathbf{0.79}^{*}$	**0.45**
	$f_{0,\mathrm{tr}}$		**0.49**	0.04	0.18	$\mathbf{0.76}^{*}$	**0.37**	**0.56**
	f_0 $\mathrm{DL}_{\mathrm{min}}$			0.18	0.00	$\mathbf{0.52}^{*}$	**0.44**	0.19
	f_0 $\mathrm{DL}_{\mathrm{max}}$				0.35	0.02	0.08	0.00
	m					0.17	0.10	0.07
	$f_{0,\mathrm{PE}}$						**0.51**	0.23
	$f_{m,\mathrm{tr}}$							0.33
Two levels for each NH listener N=17	$\mathrm{HL}_{1.5\mathrm{k}}$	$\mathbf{0.46}^{*}$	$\mathbf{0.39}^{*}$	0.23	0.04	N/A	0.15	N/A
	$f_{0,\mathrm{tr}}$		$\mathbf{0.51}^{*}$	0.01	0.14	N/A	$\mathbf{0.31}^{*}$	N/A
	f_0 $\mathrm{DL}_{\mathrm{min}}$			$\mathbf{0.38}^{*}$	0.01	N/A	$\mathbf{0.37}^{*}$	N/A
	f_0 $\mathrm{DL}_{\mathrm{max}}$				0.19	N/A	0.03	N/A
	m					N/A	0.06	N/A
	$f_{0,\mathrm{PE}}$						N/A	N/A
	$f_{m,\mathrm{tr}}$							N/A

son correlation coefficients (R^2) values are listed, along with an indication of the significance of each correlation (boldface indicates $p<0.05$), for analyses conducted with one data point per listener (N=14; only the low-level NH data included), only the HI listeners (N=11) and, where applicable, all data including two stimulus levels for each NH listener (N=17). Partial correlations, with the contribution of TEN level removed, were also computed to control for the possibility that observed correlations were due to differences in stimulus level rather than hearing impairment. Asterisks in Table IV indicate significant partial correlations ($p<0.05$, partial R^2 values not shown). The term N/A reflects the fact that NH listeners were only tested at the low level for one of the measures in a given correlation, so that 17 data points were not available. The R^2 and p values shown in each correlation plot (Figs. 6–8) are based on 14 data points, one for each NH listener tested at the low level and one for each HI listener. Correlations reported in the text are based on the same 14 data points, unless otherwise specified.

1. Relationships between the f_0 DL transition point and measures of frequency selectivity

Figure 6 shows the data and regression line for the log-transformed $f_{0,\mathrm{tr}}$ plotted as a function of $\mathrm{HL}_{1.5\mathrm{k}}$ and each of the three log-transformed frequency selectivity estimates. The $f_{0,\mathrm{tr}}$ was significantly correlated with $\mathrm{HL}_{1.5\mathrm{k}}$ [Fig. 6(a)], further supporting the conclusion that the deficit in f_0 discrimination performance is related to hearing impairment. The $f_{0,\mathrm{tr}}$ was also significantly correlated with each of the three estimates of peripheral frequency selectivity. The correlation between $f_{0,\mathrm{tr}}$ and $f_{0,\mathrm{PE}}$ (as well as between $f_{0,\mathrm{tr}}$ and both $\mathrm{HL}_{1.5\mathrm{k}}$ and $f_{m,\mathrm{tr}}$ in the N=17 case) remained significant with TEN level removed from the analysis (asterisks in Table IV), suggesting that the correlation between the $f_{0,\mathrm{tr}}$ and frequency selectivity was probably due to hearing impairment

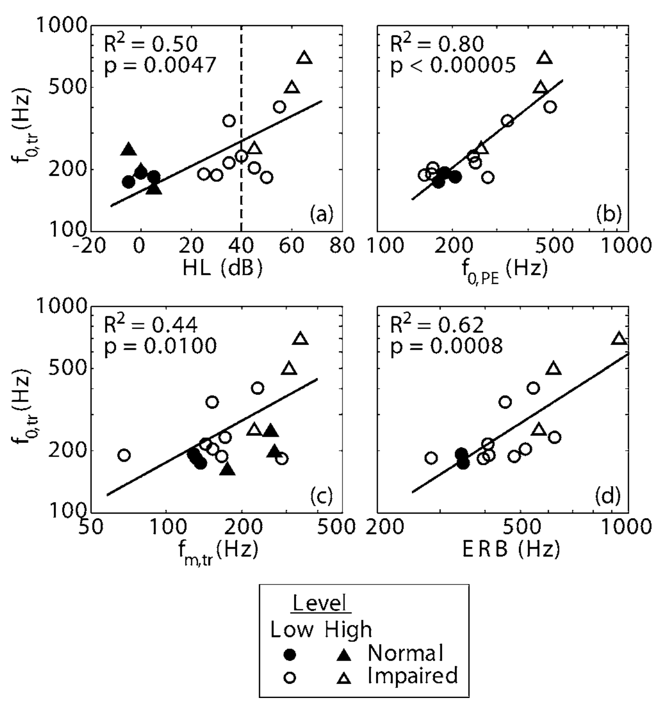

FIG. 6. The $f_{0,\mathrm{tr}}$ was significantly correlated with (a) the audiometric threshold at 1.5 kHz ($\mathrm{HL}_{1.5\mathrm{k}}$), and each of the three estimates of frequency selectivity: (b) $f_{0,\mathrm{PE}}$, (c) $f_{m,tr}$, and (d) ERB. The NH data for stimuli presented at the high level (filled triangles) were not included in the regression analyses. The vertical dashed line in (a) represents the cutoff between "normal-to-mild" and "moderate" hearing loss groups that yielded significantly different regression coefficients (see Sec. V B 1).

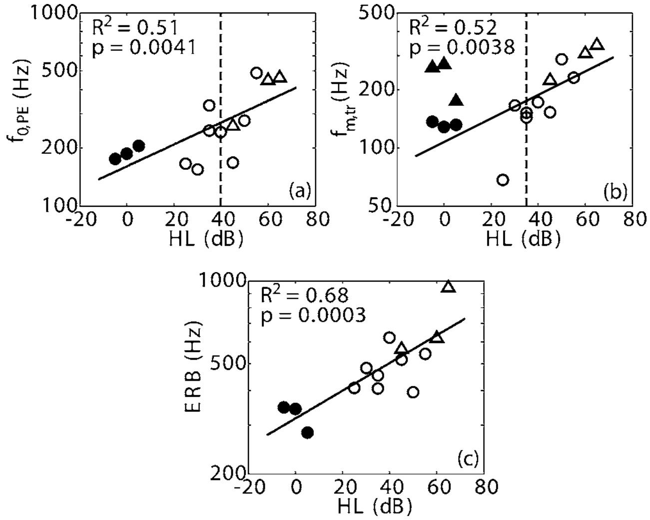

FIG. 7. The three estimates of frequency selectivity, (a) $f_{0,\mathrm{PE}}$, (b) $f_{m,\mathrm{tr}}$, and (c) ERB, were each significantly correlated to $\mathrm{HL}_{1.5\mathrm{k}}$. Vertical dashed lines in (a) and (b) represent the cutoffs between "normal-to-mild" and "moderate" hearing loss groups that yielded significantly different regression coefficients (see Sec. V B 1). See the legend of Fig. 6 for symbol definitions.

per se and not to variation in stimulus level.

Figure 7 shows that each of the measures of frequency selectivity were also significantly correlated with the degree of hearing loss. To investigate the possibility that the correlations between $f_{0,\mathrm{tr}}$ and each estimate of frequency selectivity could be an epiphenomena of their common dependencies on $\mathrm{HL}_{1.5\mathrm{k}}$, partial regression analyses were performed by removing from the analyses the contribution of $\mathrm{HL}_{1.5\mathrm{k}}$ to the variance in $f_{0,\mathrm{tr}}$ or f_0 $\mathrm{DL}_{\mathrm{min}}$. None of the resulting partial correlations involving $f_{m,\mathrm{tr}}$ or ERB as the frequency selectivity variable was significant ($p > 0.05$). However, with $f_{0,\mathrm{PE}}$ as the frequency selectivity variable, the partial correlation with $f_{0,\mathrm{tr}}$ was statistically significant ($R^2 = 0.78, p < 0.005$), suggesting that the correlation between $f_{0,\mathrm{tr}}$ and $f_{0,\mathrm{PE}}$ was not an epiphenomenon of their common dependence on $\mathrm{HL}_{1.5\mathrm{k}}$.

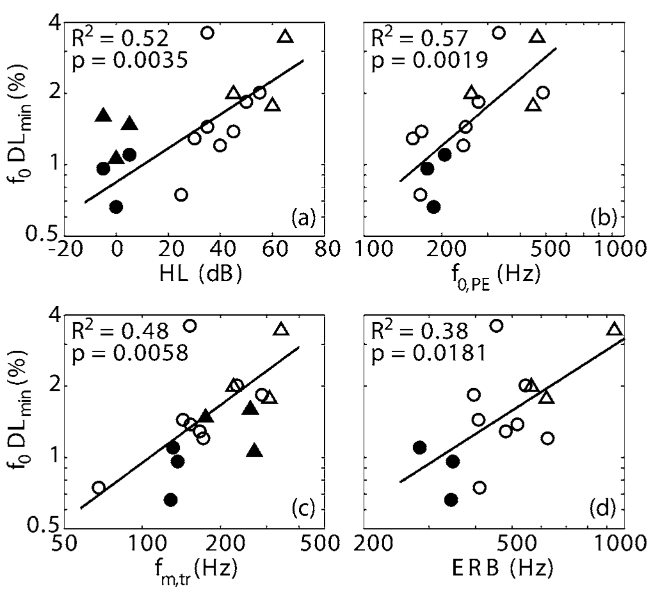

FIG. 8. The f_0 $\mathrm{DL}_{\mathrm{min}}$ was significantly correlated with (a) the audiometric threshold at 1.5 kHz ($\mathrm{HL}_{1.5\mathrm{k}}$), and each of the three estimates of frequency selectivity: (b) $f_{0,\mathrm{PE}}$, (c) $f_{m,\mathrm{tr}}$, and (d) ERB. See the legend of Fig. 6 for symbol definitions.

One additional aspect of the data that supports the idea that the $f_{0,\mathrm{tr}}$ depends on frequency selectivity *per se* is that the $f_{0,\mathrm{tr}}$ values show a similar dependence on HL as two of the three estimates of frequency selectivity. Consistent with earlier studies of frequency selectivity in HI listeners (Tyler *et al.*, 1983; Nelson, 1991; Moore, 1998; Moore *et al.*, 1999), hearing loss had little effect on the $f_{0,\mathrm{tr}}$, $f_{m,\mathrm{tr}}$ or $f_{0,\mathrm{PE}}$ until HL increased above approximately 30–40 dB HL [Figs. 6(a), 7(a), and 7(b)], suggesting that $f_{0,\mathrm{tr}}$ is better predicted by frequency selectivity than by audiometric threshold. To quantify this observation, the data were divided into two categories based on the degree of hearing loss at 1.5 kHz. Listeners with audiometric thresholds $<$40 dB HL [vertical dashed line in Figs. 6(a) and 7(a)] were assigned to the "normal-to-mild" group (N=7), while those with thresholds $\geqslant$40 dB HL were assigned to the "moderate" group (N=7). A Potthoff (1966) analysis showed the regression coefficients to be statistically different ($p < 0.05$) between the two groups for the $f_{0,\mathrm{tr}}$ and $f_{0,\mathrm{PE}}$, and for $f_{m,\mathrm{tr}}$, when the cutoff between the two groups was defined at 35 dB HL [vertical dashed line in Fig. 7(b)] instead of 40 dB HL. Regression coefficients were not significantly different between the two groups ($p = 0.55$) for the ERB measure.

2. f_0 DL_{max}, f_0 DL_{min}, and *m*

The f_0 $\mathrm{DL}_{\mathrm{min}}$ was significantly correlated with $\mathrm{HL}_{1.5\mathrm{k}}$ and each of the three measures of frequency selectivity (Fig. 8), although the correlations with $\mathrm{HL}_{1.5\mathrm{k}}$ and with ERB were weak and became nonsignificant when the NH data were removed from the analysis. The correlations between f_0 $\mathrm{DL}_{\mathrm{min}}$ and $\mathrm{HL}_{1.5\mathrm{k}}$ and between f_0 $\mathrm{DL}_{\mathrm{min}}$ and both $f_{0,\mathrm{PE}}$ and $f_{m,\mathrm{tr}}$ remained significant with TEN level removed from the analysis (asterisks in Table IV), suggesting that the observed effects are related to the hearing loss and not to variation in stimulus level. However, none of the correlations between f_0 $\mathrm{DL}_{\mathrm{min}}$ and the three frequency selectivity estimates remained significant when $\mathrm{HL}_{1.5\mathrm{k}}$ was partialled out ($p > 0.05$), leaving open the possibility that f_0 $\mathrm{DL}_{\mathrm{min}}$ may not be dependent on frequency selectivity *per se*.

Estimates of f_0 $\mathrm{DL}_{\mathrm{max}}$ were significantly correlated with $\mathrm{HL}_{1.5\mathrm{k}}$ (Table IV; plot not shown), suggesting that SNHL is associated with an impairment in f_0 discrimination for unresolved harmonics. However, the f_0 $\mathrm{DL}_{\mathrm{max}}$ was not significantly correlated with any of the three measures of peripheral frequency selectivity ($p > 0.05$). This suggests that if there is a deficit in f_0 $\mathrm{DL}_{\mathrm{max}}$ related to HI, then some mechanism not directly related to peripheral frequency selectivity, such as the ability to process envelope modulations, may be responsible. Estimates of *m* were not significantly correlated with any other summary measure.

3. Relationships between the f_0 DL measures

The $f_{0,\mathrm{tr}}$ was found to be significantly correlated with the f_0 $\mathrm{DL}_{\mathrm{min}}$, mirroring a result observed by Bernstein and Oxenham (2006) whereby both the $f_{0,\mathrm{tr}}$ and the f_0 $\mathrm{DL}_{\mathrm{min}}$ increased at a high stimulus level (~80 dB SPL) in NH listeners. This raises the possibility that more poorly encoded resolved component frequencies (as evidenced by the elevated f_0 $\mathrm{DL}_{\mathrm{min}}$) indirectly caused the $f_{0,\mathrm{tr}}$ effect by reducing the auditory system's ability to process resolved harmonics. However, the correlations between $f_{0,\mathrm{tr}}$ and both the $f_{0,\mathrm{PE}}$ and the ERB remained significant ($p<0.05$) when the influence of f_0 $\mathrm{DL}_{\mathrm{min}}$ was controlled in partial correlation analyses, suggesting that the $f_{0,\mathrm{tr}}$ effect was not a direct result of poor frequency encoding of individual partials (the partial correlation between $f_{0,\mathrm{tr}}$ and $f_{m,\mathrm{tr}}$ was not significant). The f_0 $\mathrm{DL}_{\mathrm{min}}$ and f_0 $\mathrm{DL}_{\mathrm{max}}$ were also significantly correlated, suggesting that hearing-impaired listeners experience an overall deficit in f_0 discrimination performance.

4. Alternative transition-point definitions

In the correlation analyses described above, the various summary measures ($f_{0,\mathrm{tr}}, f_{m,\mathrm{tr}}, f_{0,\mathrm{PE}}$) were calculated based on the midpoints of the transitions between best and worst performance levels. From a mathematical viewpoint, the midpoint is most accurately defined, because the slope of a sigmoid is steepest at that point. However, to assess harmonic resolvability, other points along the function might be more appropriate. For instance, an alternative measure might consider harmonics to be unresolved as soon as a phase effect first occurs (Moore *et al.*, 2006). The regression analyses described above were recalculated with the transition points defined as the f_0 for which performance was as follows: for the $f_{0,\mathrm{tr}}$, 10% of the distance (on a log scale) between f_0 $\mathrm{DL}_{\mathrm{min}}$ and f_0 $\mathrm{DL}_{\mathrm{max}}$; for the $f_{0,\mathrm{PE}}$, 10% the distance (on a log scale) between the minimum and maximum f_0 DL phase effect; and for the $f_{m,\mathrm{tr}}$, 10% of the distance (in percentage points) between the chance (33%) and perfect (100%) performance. The results of this analysis were largely the same (with regard to the significance of bivariate correlations) as those presented in Table IV, suggesting that the correlations observed between the various summary measures are robust with respect to the way in which the transition points are defined. There were, however, four exceptions. With the transitions defined based on the 10% points instead of the midpoints of the individual fitted curves, correlations became significant ($p<0.05$) between f_0 $\mathrm{DL}_{\mathrm{max}}$ and $f_{0,\mathrm{tr}}$ in the $\mathrm{N}=14$ ($R^2=0.34$) and $\mathrm{N}=17$ ($R^2=0.31$) analyses, and between f_0 $\mathrm{DL}_{\mathrm{max}}$ and $f_{0,\mathrm{PE}}$ ($R^2=0.30$) in the $\mathrm{N}=14$ analysis. For this alternative definition, the correlation between $f_{0,\mathrm{tr}}$ and the ERB in the $\mathrm{N}=11$ analysis was no longer significant ($p=0.08$).

VI. DISCUSSION

A. Relationship between f_0 discrimination and frequency selectivity

1. The f_0 DL transition point

The strong correlations between the $f_{0,\mathrm{tr}}$ and each of the three measures of frequency selectivity support the hypothesis that the spacing between harmonics required for good f_0 discrimination performance is related to peripheral frequency selectivity. The significant correlations between f_0 discrimination and frequency selectivity were not a result of generally poor performance in psychoacoustic tasks by HI listeners, because *good* performance in modulation discrimination (Experiment 2, large $f_{m,\mathrm{tr}}$) was correlated with *poor* performance in f_0 discrimination (Experiment 1, large $f_{0,\mathrm{tr}}$ and f_0 $\mathrm{DL}_{\mathrm{min}}$). The significant correlations between the $f_{0,\mathrm{tr}}$ and frequency selectivity most likely represent a direct relationship between the two types of measure and not simply a common dependence on audiometric thresholds, as evidenced by the significant partial correlation between the $f_{0,\mathrm{tr}}$ and the $f_{0,\mathrm{PE}}$ when controlling for $\mathrm{HL}_{1.5\mathrm{k}}$, as well as the similar nonlinear dependence on $\mathrm{HL}_{1.5\mathrm{k}}$ exhibited by both types of measure [Fig. 6(a), 7(a) and 7(b)]. Furthermore, the data of Bernstein and Oxenham (2006) in NH listeners show that stimulus level affected both frequency selectivity and the $f_{0,\mathrm{tr}}$ in the same way as hearing loss in the current study. Thus, frequency selectivity, the common denominator between these two studies, is likely to be responsible for the observed increases in $f_{0,\mathrm{tr}}$ and f_0 $\mathrm{DL}_{\mathrm{min}}$ in both cases.

2. Pure-tone FDLs and the f_0 DL_{min}

The current study also found significant correlations between each of the three estimates of frequency selectivity and the f_0 $\mathrm{DL}_{\mathrm{min}}$. As the f_0 $\mathrm{DL}_{\mathrm{min}}$ estimate was tightly coupled to the 1500-Hz pure-tone FDLs, the log-transformed FDLs were also significantly correlated to each of the three log-transformed estimates of frequency selectivity ($f_{0,\mathrm{PE}}$: $R^2=0.55$, $p<0.005$; $f_{m,\mathrm{tr}}$: $R^2=0.51$, $p<0.005$; ERB: $R^2=0.32$, $p<0.05$). This result conflicts with several previous studies of the relationship between pure-tone frequency discrimination and peripheral frequency selectivity that have found only weak or nonsignificant correlations between the two types of measure (e.g., Tyler *et al.*, 1983; Moore and Glasberg, 1986; Moore and Peters, 1992).

One possible source of this discrepancy is the method of estimating frequency selectivity. In the Tyler *et al.* (1983) study, the small number of data points measured (three) on the PTC may have limited the accuracy of this frequency selectivity measure. Moore and Peters (1992) and Moore and Glasberg (1986) used an ERB measure derived from notched-noise data. This method yielded the weakest correlation with the FDL data in the current study, which may be due to differences in stimulus type or to the increased variability resulting from the additional step of fitting the masking data to a model auditory filter.

The use of background noise in the current study may also underlie the departure from previous investigations that found weak or absent correlations between FDLs and frequency selectivity when stimuli were presented in quiet. In NH listeners, reduced frequency selectivity at higher stimulus levels has been shown to negatively affect FDLs for pure tones presented in a background noise (e.g., Dye and Hafter, 1980; Bernstein and Oxenham, 2006) but not in isolation (e.g., Wier *et al.*, 1977). It may be that in the absence of a background noise, a higher-level stimulus excites a larger number of auditory nerve fibers, thereby distributing information for frequency discrimination over a broader tonotopic region and increasing the amount of information present (Green and Luce, 1974) in a way that offsets the effects of a reduction in frequency selectivity. Florentine and Buus (1981) invoked a similar idea involving the spread of excitation to explain the deviation from Weber's law in pure-tone intensity discrimination. The use of TEN in the current study to reduce differences in SL and SPL across listeners may have also reduced the influence of absolute level (e.g. Bernstein and Oxenham, 2006) and sensation level (e.g. Hoekstra, 1979) on FDLs. In contrast, Moore and Glasberg (1986) and Tyler *et al.* (1983) presented pure tones to HI listeners at a constant SPL (80 and 94 dB, respectively), with the equivalent SL ranging from approximately 50 to 80 dB across listeners, respectively. Moore and Peters (1992) presented tones at a constant 25 dB SL, yielding an approximately 50 dB SPL range across the HI listeners.

Finally, the pure-tone frequency discrimination measurements reported here were only performed at a single frequency, 1500 Hz. It is not known whether similar effects would be obtained with hearing loss at lower frequencies. Dye and Hafter (1980) showed that for lower-frequency tones (500 and 1000 Hz), increasing the level of both the tone and the background noise tended to improve rather than impair frequency discrimination performance, suggesting that frequency selectivity may have less effect on lower-frequency tones. On the other hand, level is known to have less effect on frequency selectivity at low frequencies (1000 Hz and below) than at high frequencies (Baker *et al.*, 1998). Thus, the results of Dye and Hafter (1980) at low frequencies may reflect the reduction or absence of an effect of level on frequency selectivity rather than the absence of an effect of frequency selectivity on FDLs.

B. Possible role of temporal fine structure

The results clearly indicate a significant correlation between f_0 discrimination and frequency selectivity in the same listeners. Nevertheless, correlation is not causation, and the question remains whether the f_0 transition point depends on harmonic resolvability or some other aspect of auditory processing. One possibility is that impaired f_0 DLs may reflect a deficit in fine-structure processing. There are at least two ways in which such an impairment could arise. First, a reduction in fine-structure information could be the direct result of the impaired frequency selectivity in the HI listeners. Moore *et al.* (2006) argued that the transition from accurate to poor f_0 discrimination as a function of harmonic number in NH hearing listeners may reflect a reduction in the effectiveness of fine-structure coding as harmonics begin to interact, rather than a reduction in the resolvability of individual harmonics. With reduced frequency selectivity in HI listeners, harmonics would also be more likely to interact, possibly reducing the effectiveness of fine-structure coding. Second, HI listeners may have an inherent fine-structure impairment, perhaps due to a reduction of phase locking in the auditory nerve (e.g., Woolf *et al.*, 1981). Recent psychophysical evidence from interaural phase-difference (Lacher-Fougére and Demany, 2005) and low-rate FM discrimination (Buss *et al.*, 2004) measures in HI listeners support this idea. Because the current study did not perform psychophysical measures thought to directly depend on temporal fine-structure processing, the role of temporal fine-structure deficits in the observed f_0 discrimination impairment remains speculative.

C. Modulation discrimination

Some HI listeners showed better modulation discrimination performance than the NH listeners, consistent with the hypothesis that poorer frequency selectivity should yield better performance in this task. Nevertheless, the performance of the HI listeners was not as much better relative to the NH listeners as would be expected based on the f_0 DL results if both the $f_{0,\text{tr}}$ and the $f_{m,\text{tr}}$ reflected frequency selectivity. In Fig. 6(c), the $f_{m,\text{tr}}$ for NH listeners tested at the higher level (filled triangles) generally fell to the right of the regression line, indicating that NH listeners performed better at modulation discrimination at this level than would be predicted from their f_0 DL data based on the relationship between $f_{0,\text{tr}}$ and $f_{m,\text{tr}}$ for the other 14 data points. This observation was supported by a significant one-tailed independent-sample t test, adjusted for unequal variances, comparing NH and HI listeners based on the log-transformed ratio $f_{0,\text{tr}}/f_{m,\text{tr}}$ $[t(13.7)=1.84, p<0.05]$. One interpretation of this result is that HI listeners may have some deficit in modulation processing that reduces their discrimination performance to below what they might achieve based on peripheral filter bandwidths alone. HI listeners do not generally show deficits in modulation processing when signals are presented to NH and HI listeners at an equal SL (Bacon and Gleitman, 1992). However, the wideband background noise was not used in Experiment 2, so that signals were presented at a higher SL for NH listeners. Alternatively, the relatively small $f_{m,\text{tr}}$ (relative to $f_{0,\text{tr}}$) in some HI listeners may reflect an absolute upper f_m limitation that would be experienced by any listener, not just HI listeners. For instance, it is known that modulation processing performance begins to deteriorate even in NH listeners for f_m's greater than about 150 Hz, independent of auditory filter bandwidth (Kohlrausch *et al.*, 2000). Because of the possible influence of limitations in post-filtering modulation detection efficiency, this task may not provide a fully accurate estimate of frequency selectivity (see, e.g., Moore and Sek, 1995).

Another aspect of the modulation discrimination data that may be related to a limitation in modulation processing, due either to SNHL or an absolute f_m limit, is that $f_{m,\text{tr}}$ estimates were generally smaller than $f_{0,\text{tr}}$ estimates. This result is reflected in the regression analysis (N=17), where the estimate of the linear regression coefficient (B_1) was significantly less than unity (0.56 with 95% confidence interval ±0.42). [While it could be argued (see Sec. V B 2) that the 10% point rather than the midpoint of the f_0 DL and f_m discrimination transitions may provide a more appropriate estimate of the limits of harmonic resolvability, the regression coefficient in this case was still less than unity, although not significantly so (0.64±0.42)]. This would mean that the limit of harmonic resolvability, as estimated by the modulation discrimination task, occurs at a lower f_0 (*higher* harmonic number) than the $f_{0,\text{tr}}$. One possible interpretation of this discrepancy is that the $f_{m,\text{tr}}$, which relies on wide peripheral filters for good performance, provides an *upper* limit on the extent of harmonic resolvability, whereas estimates based on listeners' ability to hear out harmonics (Plomp, 1964; Moore and Ohgushi, 1993; Bernstein and Oxenham, 2003;

2006) or phase effects on f_0 DLs (Section V A 3; Moore *et al.*, 2006) which rely on narrow filters for better performance, provide a *lower* limit.

D. Did listeners extract the f_0?

With the f_0 discrimination paradigm employed in Experiment 1, it is possible that listeners could have performed the discrimination task by comparing the frequencies of individual resolved harmonics rather than by comparing the pitch of the missing f_0. However, Moore and Glasberg (1990b) demonstrated that NH listeners are unable to ignore the pitch of the missing f_0 in making sequential comparisons between the frequencies of individual partials, in that listeners performed much worse at discriminating the frequencies of the lowest harmonics for sequential harmonic complexes with different f_0's than for complexes with the same f_0. While this result strongly argues that NH listeners do not perform f_0 discrimination based on the frequencies of individual resolved components, we cannot rule out this possibility for the HI listeners. It is especially likely that the worst performing HI listeners may have based their judgments on individual partials. For example, listeners 17 and I9(r) did not achieve f_0 DL_{min} until f_0's reached 750 Hz or even 1500 Hz—respectively, f_0's that approach or exceed the limit of the existence region for the pitch of the missing f_0 (Plomp, 1964). Roving the spectral region of the harmonic complex can reduce the usefulness of a cue based on the lowest harmonic present (Houtsma and Smurzynski, 1990; Bernstein and Oxenham, 2003). However, in the case of the poorest performing hearing-impaired listeners, the large rove range necessary to eliminate the spectral cue could result in highly distracting changes in the timbre of the complexes, which are known to negatively affect pitch discrimination (Moore and Glasberg, 1990b; Moore and Moore, 2003).

E. Perceptual implications for HI listeners

The results shown here indicate that listeners with SNHL experience a deficit in f_0 processing, directly related to a loss of peripheral frequency selectivity, which manifests itself in at least three ways. First, a larger spacing between adjacent harmonics is needed to yield the smallest possible f_0 DLs for a given spectral region, implying that in everyday listening conditions a larger proportion of stimulus f_0's will yield a weak pitch percept in these listeners. Second, even when harmonics are widely separated, the f_0 DLs are larger (poorer) than in NH listeners. Finally, the results of Experiment 1 also show that listeners with SNHL had a higher $f_{0,PE}$ than normal, meaning that these listeners will experience potentially detrimental effects of component phase on f_0 discrimination over a larger range of f_0's. This effect may be of particular importance in a reverberant environment, where a heterogeneous mixture of reflection delays tends to "smear" the temporal envelopes (Houtgast *et al.*, 1980; Steeneken and Houtgast, 1980) at the output of auditory filters excited by unresolved harmonics (Qin and Oxenham, 2005). With wider filters, listeners with SNHL will be more susceptible to the negative impact of reverberation phase randomization on f_0 discrimination.

F. Implications for pitch models

The current findings corroborate the previous findings of Bernstein and Oxenham (2006) showing that in NH listeners, f_0 DL_{min} and $f_{0,tr}$ increased as a function of stimulus level in the same way as peripheral frequency selectivity. The current study extends this finding by establishing a relationship between f_0 discrimination and frequency selectivity in a large enough population of NH and HI listeners to yield significant correlations between the two measures. Because the findings of the two studies are similar with respect to the relationship between f_0 discrimination and frequency selectivity, the implications for models of pitch perception of the current HI results are the same as those discussed in the previous manuscript (for full discussion, see Bernstein and Oxenham, 2006). To summarize, these results are consistent with any pitch model that relies on peripheral frequency selectivity to explain why low-order harmonics yield better f_0 DLs than high-order harmonics. This includes spectral (e.g., Goldstein, 1973) and spectro-temporal (Shamma and Klein, 2000; Cedolin and Delgutte, 2005) models that use place or timing information to extract the frequencies of individual resolved harmonics, as well as a recent version of the autocorrelation model (de Cheveigné and Pressnitzer, 2006) that depends on temporal response characteristics of auditory filters that are related to the filter bandwidths.

VII. SUMMARY AND CONCLUSIONS

Listeners with SNHL experience a deficit in f_0 discrimination that manifests itself in terms of an increase in the minimum spacing between harmonics required for f_0 DLs to transition from large (poor) to small (good). The f_0 DL transition point was significantly correlated to three different estimates of frequency selectivity, supporting the hypothesis that good f_0 discrimination performance depends on sharp frequency selectivity, and that listeners with SNHL experience a deficit in f_0 processing due to a reduction in frequency selectivity. Additionally, the best f_0 discrimination performance achieved by HI listeners was worse than that attained by NH listeners even when harmonics were spaced widely enough in frequency to yield relatively good f_0 discrimination performance associated with resolved harmonics. This effect, also observed for pure tones, was also correlated with two estimates of frequency selectivity in HI listeners, suggesting a possible role for frequency selectivity in the frequency encoding of individual resolved harmonics. These results support spectral and spectro-temporal theories of pitch perception that rely on frequency selectivity to extract the frequencies of individual resolved harmonics, but may also be consistent with a place-dependent temporal model of pitch perception where the range of detectable periodicities is limited by the impulse response durations of cochlear filters.

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[1]Some listeners with audiometric thresholds at 1 and 2 kHz within 5 dB HL of each other were not tested at 1.5 kHz. For these listeners, the 1.5 kHz threshold is taken as the mean of the 1 and 2 kHz thresholds.

[2]Listener I1 had a low-frequency loss with near-normal thresholds at 3 and 4 kHz (10 and 20 dB HL, respectively), but impaired thresholds at lower frequencies (50 dB HL at 1 and 2kHz). Listener I2 had a notched loss, with impaired thresholds at 1.5 and 2 kHz (45 and 50 dB HL, respectively), but a mild loss of 25 dB HL at 4 kHz.

[3]For NH listener N1, the TEN and stimulus levels were each reduced by 5 dB for the 75- and 125-Hz f_0's. For NH listener N3, the stimulus level was reduced by 3 dB for the 75-Hz f_0, but the TEN was kept at 65 dB SPL/$\mathrm{ERB_N}$. For HI listener I9(r), who completed more f_0 conditions than the other listeners, the 75-Hz f_0 conditions were not tested.

[4]HI $f_{0,\mathrm{PE}}$ and ERB estimates measured at the high stimulus level were compared to the NH low-level estimates because no high-level NH data were available (asterisks in Table III).

[5]The sigmoid function was defined as:

$$\log[f_0DL(\%)] = \log(f_0DL_{\max}) + \frac{1}{\sqrt{\pi}}\log\left(\frac{f_0DL_{\min}}{f_0DL_{\max}}\right)\int_{m\,\log(f_0/f_{0,\mathrm{tr}})}^{\infty} e^{-[\log(f_0)]^2} d[\log(f_0')]. \quad (1)$$

[6]The assumption that the pure-tone case will yield the smallest possible DL may be questionable because the presence of multiple resolved harmonics could yield additional f_0 information. However, two-tailed t tests indicated that for each listener and level, with one exception, the f_0 DL at the largest f_0 tested (500, 750, or 1500 Hz) was not significantly different ($p > 0.05$) from the FDL for the 1500-Hz pure tone. [The exception was listener I1, where the f_0 DL at 750 Hz, the largest f_0 tested in this listener, was significantly smaller than the 1500 Hz pure-tone FDL ($P < 0.01$).]

[7]For the NH listeners, the data at 500 Hz were not included in the PE analysis because sine-phase measurements were not performed at that f_0.

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