The effect of hearing loss on the resolution of partials and fundamental frequency discrimination

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The relationship between the ability to hear out partials in complex tones, discrimination of the fundamental frequency (F0) of complex tones, and frequency selectivity was examined for subjects with mild-to-moderate cochlear hearing loss. The ability to hear out partials was measured using a two-interval task. Each interval included a sinusoid followed by a complex tone; one complex contained a partial with the same frequency as the sinusoid, whereas in the other complex that partial was missing. Subjects had to indicate the interval in which the partial was present in the complex. The components in the complex were uniformly spaced on the ERB_N-number scale. Performance was generally good for the two "edge" partials, but poorer for the inner partials. Performance for the latter improved with increasing spacing. F0 discrimination was measured for a bandpass-filtered complex tone containing low harmonics. The equivalent rectangular bandwidth (ERB) of the auditory filter was estimated using the notched-noise method for center frequencies of 0.5, 1, and 2 kHz. Significant correlations were found between the ability to hear out inner partials, F0 discrimination, and the ERB. The results support the idea that F0 discrimination of tones with low harmonics depends on the ability to resolve the harmonics. © *2011 Acoustical Society of America*.
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I. INTRODUCTION

It is well established that cochlear hearing loss adversely affects the ability to detect changes in the fundamental frequency (F0) of complex tones (Hoekstra and Ritsma, 1977; Moore and Glasberg, 1988b; Moore and Peters, 1992; Arehart, 1994; Arehart and Burns, 1999; Moore and Moore, 2003a; Bernstein and Oxenham, 2006b); for reviews see Moore and Carlyon (2005) and Moore (2007). This has important consequences, as the perception of differences in F0 contributes to the ability to identify the speech of one talker in the presence of another talker (Brokx and Nooteboom, 1982; Scheffers, 1983; Arehart *et al.*, 1997; Summers and Leek, 1998; Darwin and Hukin, 2000) and is also critical for the appreciation of music.

The reasons why hearing loss leads to impaired F0 discrimination are unclear. Several factors have been proposed to play a role. For complex tones containing low harmonics, which would be resolved in the auditory system of a normal-hearing listener (Plomp, 1964), the possible factors include: a reduced ability to resolve the harmonics as a consequence of reduced frequency selectivity (Glasberg and Moore, 1986; Moore and Glasberg, 1988a, 1990; Moore and Peters, 1992; Bernstein and Oxenham, 2006b); a reduced ability to discriminate changes in the frequencies of resolved or partially resolved harmonics (Moore *et al.*, 1984; Bernstein, 2006; Gockel *et al.*, 2007); and reduced sensitivity to the temporal fine structure (TFS) of resolved or partially resolved harmonics (Moore *et al.*, 2006a; Hopkins and Moore, 2007). These factors are interlinked, as the ability to hear out harmonics and to judge their pitch may depend partly on sensitivity to TFS (Moore and Ohgushi, 1993; Hartmann and Doty, 1996; Moore *et al.*, 2006c; Moore and Gockel, 2011), as well as on frequency selectivity. For complex tones containing only high, unresolved harmonics, possible reasons why hearing loss leads to impaired F0 discrimination are: a reduced ability to process TFS information (Moore *et al.*, 2006a; Hopkins and Moore, 2007), and a reduced ability to process temporal envelope information (Formby, 1985). In addition, for all types of complex tones, neural coding may be "noisier" or less precise than normal due to loss of function of inner hair cells and/or neurons (Huss and Moore, 2003; 2005; Moore, 2007). The present study examined the relationship between the ability to hear out partials in complex tones, discrimination of the fundamental frequency (F0) of complex tones, and frequency selectivity, for subjects with mild-to-moderate cochlear hearing loss. The main goal was to assess whether the ability to discriminate changes in F0 of complex tones containing low harmonics is correlated with the ability to hear out partials in complex tones.

Several studies have examined whether there is a relationship between F0 discrimination and frequency selectivity for hearing-impaired listeners. Most have not found a strong relationship (Hoekstra, 1979; Glasberg and Moore, 1989; Moore and Glasberg, 1990; Moore and Peters, 1992). However, Bernstein and Oxenham (2006b) did find a relationship. Their study was based on the finding that discrimination of F0 worsens when the number, N, of the lowest harmonic in a complex tone increases above about 7, reaching a plateau when N is about 14–15 (Hoekstra and Ritsma, 1977; Houtsma and Smurzynski, 1990; Kaernbach and Bering, 2001; Bernstein

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and Oxenham, 2003, 2006a; Moore *et al.*, 2006b). This has often been characterized as reflecting the transition from resolved to unresolved harmonics (Houtsma and Smurzynski, 1990; Shackleton and Carlyon, 1994); it is often assumed that F0 discrimination is good when some resolved harmonics are present, and poor when no harmonics are resolved. Another possible interpretation is that the worsening of F0 discrimination as N is increased above about 7 reflects a progressive loss of ability to use TFS information (Moore *et al.*, 2006b; Moore, 2008; Bernstein and Oxenham, 2005; Ives and Patterson, 2008; Moore and Gockel, 2011). Bernstein and Oxenham (2006b) assumed that the transition from good to poor discrimination reflected the change from resolved to unresolved harmonics and therefore indirectly reflected frequency selectivity. They estimated the value of N at which the transition occurred by passing complex tones through a fixed bandpass filter (passband from 1500 to 3500 Hz) and measuring difference limens for F0 discrimination (F0DLs) as a function of F0. The value of F0 at which the transition occurred, F0tr, was significantly correlated with three measures of frequency selectivity: (1) the highest F0 at which the F0DLs were influenced by relative component phase (Houtsma and Smurzynski, 1990; Shackleton and Carlyon, 1994); (2) the highest modulation frequency for which amplitude modulation and quasifrequency modulation with the same modulation index were discriminable (Schorer, 1986; Sek and Moore, 1994); and (3) the bandwidth of the auditory filter estimated using the notched-noise method (Patterson *et al.*, 1982; Glasberg and Moore, 1990; Rosen *et al.*, 1998). Poorer frequency selectivity was associated with higher values of F0tr. Bernstein and Oxenham (2006b) also found that these measures of frequency selectivity were correlated with the "best" F0DL achieved at high F0s, for which the harmonics were most likely to have been resolved.

Bernstein and Oxenham (2006b) concluded that the relatively poor F0 discrimination found for hearing-impaired listeners was partly caused by reduced frequency selectivity. They also concluded that the results supported place and place–time theories of pitch perception that assume a role for frequency selectivity in the extraction of information about the frequencies of individual resolved harmonics.

It has proved difficult to make direct measurements of the ability of hearing-impaired subjects to hear out partials from complex tones, as the tasks that have been used to assess this ability are quite complex, and can initially be difficult to perform even for subjects with normal hearing. A widely used task is based on that described by Roberts and Bregman (1991) and by Moore and Ohgushi (1993). On each trial, subjects are presented with a sinusoidal tone followed by a complex tone. The sinusoid will be referred to as the "probe." Subjects are told that the probe is close in pitch to one of the partials in the complex tone, but is actually slightly higher or lower in pitch than that partial. On half the trials, chosen at random, the probe is higher in frequency than the partial, and on the other half it is lower. Subjects are asked to indicate, by pressing the appropriate button on the response box, whether the probe is higher or lower in pitch than the "closest" partial in the complex. Often, the partial that is "probed" is varied randomly from trial to trial, and the frequencies of all partials in the complex tone are also randomly varied (roved) from trial to trial by multiplying them by a certain factor. This is done to prevent the subject from performing the task by learning the correct answer associated with a specific probe frequency (Soderquist, 1970; Bernstein and Oxenham, 2003; Moore *et al.*, 2006c).

It has been reported that good performance on tasks like this requires practice and appropriate training (Moore *et al.*, 2006c). Even after practice, performance may be affected by perceptual confusion effects, for example confusion about which partial in the complex tone to compare with the probe tone (Moore *et al.*, 2006c). We attempted to use this task with hearing-impaired listeners, but found that most had great difficulty in performing the task. Bernstein and Oxenham (2003) introduced a stimulus manipulation intended to reduce perceptual confusion effects. Both the probe tone and the "nearest" partial in the complex tone were pulsed on and off repeatedly (see also, Moore *et al.*, 2009). However, even with this manipulation, Bernstein (2006) found that hearing-impaired subjects were unable to perform the task at above-chance levels.

In the present paper we present measures of the ability of hearing-impaired subjects to hear out partials from complex tones using a method that was intended to minimize perceptual confusion effects (Experiment 1). The method did not require subjects to identify the direction of a pitch change, which is difficult for some subjects (Semal and Demany, 2006). Rather, subjects were required to indicate which of two complex tones contained a previously presented sinusoidal probe tone. The task is described in detail below.

Two additional measures were obtained for the same subjects. First, F0DLs were measured for a complex tone containing low-numbered harmonics (Experiment 2). This allowed us to assess the relationship between the ability to hear out partials and F0 discrimination. Second, measures of frequency selectivity based on the notched-noise method were obtained (Experiment 3). The results of the notched-noise method are thought not to depend strongly on the use of TFS information, as the pattern of results is similar for medium frequencies (Moore and Glasberg, 1987; Glasberg and Moore, 1990), for which TFS information is thought to be usable, and for very high frequencies (Shailer *et al.*, 1990; Zhou, 1995), for which TFS information is thought not to be usable. This allowed us to assess the relationship between the ability to hear out partials, which may be partly affected by the ability to use TFS information, and an independent measure of frequency selectivity that is less likely to be affected by the ability to use TFS information.

II. METHOD

A. Subjects

Eight subjects with hearing loss were tested. Their air-conduction audiograms are shown in Fig. 1, which also shows the age of each subject. One of the subjects (designated HI4) originally had a mixed sensorineural and conductive hearing loss in her right ear, but the conductive

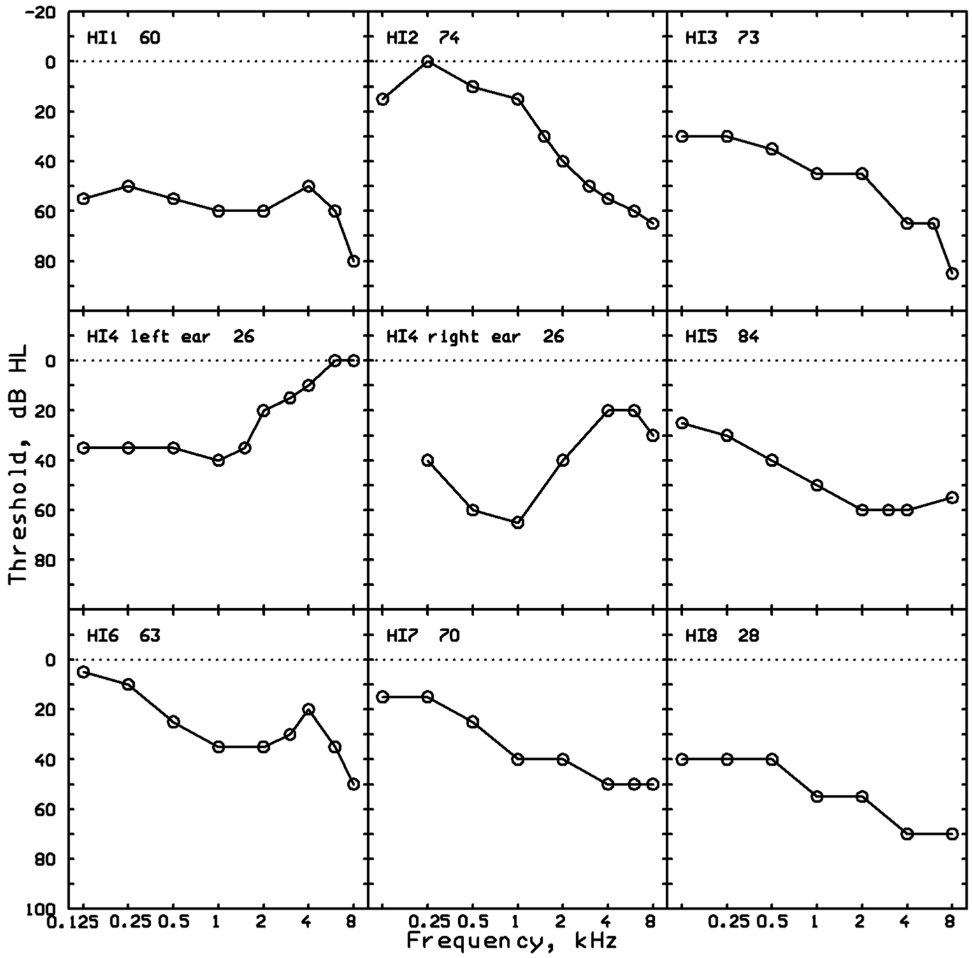

FIG. 1. Audiograms of the nine hearing-impaired ears tested. Subject HI4 was tested using each ear separately, but only one ear was tested for each of the other subjects. The number in each panel indicates the age of the subject.

component had been largely corrected by middle-ear surgery; air-conduction thresholds were about 10 dB higher than bone-conduction thresholds. The other ear of HI4 and the test ears of all other subjects had sensorineural losses, as indicated by differences between air-conduction and bone-conduction thresholds less than 10 dB. HI4 was tested using each ear separately, whereas the other subjects were tested using the ear with the least variation in audiometric thresholds across mid-range frequencies (0.5–4 kHz). HI4 had previous experience in psychoacoustic tasks, including frequency discrimination tasks. The other subjects did not have previous experience in psychoacoustic tasks. Subjects were given practice on all tasks until their performance appeared to be stable (see below for details).

For comparison, six normal-hearing subjects (all with audiometric thresholds better than 20 dB hearing loss (HL) at all audiometric frequencies) were tested on the new task for assessing the ability to hear out partials from complex tones. Six normal-hearing subjects (all with audiometric thresholds better than 20 dB HL at all audiometric frequencies) were tested on the task measuring F0DLs. Only one normal-hearing subject was common to the two experiments.

B. Equipment and stimulus generation

Stimuli were generated digitally using a Tucker-Davis Technologies (TDT) system II. The stimuli were played through a 16-bit digital-to-analog converter (TDT, DD1) at a 50-kHz sampling rate, low-pass filtered at 8 kHz (Kemo VBF8/04), attenuated (TDT, PA4), and presented via a headphone buffer (TDT, HB6), a manual attenuator (Hatfield 2125), and one earpiece of a Sennheiser HD580 headphone, which has a diffuse-field response. Levels specified are equivalent diffuse-field levels. Levels at the eardrum would have been higher for frequencies around 3000 Hz (Moore *et al.*, 1998). Subjects were tested individually in a double-walled sound-attenuating chamber.

C. Stimuli and procedure for measuring the ability to hear out partials (Experiment 1)

The ability to hear out partials was measured for complex tones with partials uniformly spaced on an ERB_N-number scale (Glasberg and Moore, 1990). The partials were therefore inharmonically spaced. This was done for two reasons. First, it reduced the tendency for the partials to fuse based on their harmonicity (Moore *et al.*, 1986). Second, the waveform of the inharmonic tones was not periodic, so it was unlikely that the results would be influenced by the specific set of random starting phases chosen for the partials (Hartmann and Goupell, 2006).

For brevity here, the ERB_N number is denoted by *Cam*, following a suggestion of Hartmann (1997). The relationship between the *Cam* value and frequency, f (Hz), was assumed to be as suggested by Glasberg and Moore (1990):

$$Cam = 21.41 \log_{10}(0.00437f + 1). \quad (1)$$

The spacings used were 1, 2, 3, and 4 *Cam*. Subject HI4 was additionally tested with a spacing of 1.5 *Cam*. The frequency of the central partial was always 1201 Hz, corresponding to *Cam* = 17. The overall frequency range of the partials in the complex tones was limited to the range 0.3–4 kHz. This meant that the number of partials varied with *Cam* spacing. The complex tones contained 11, 9, 7, and 5 partials for spacings of 1, 2, 3, and 4 *Cam*. The frequencies of all partials for each spacing used are given in Table I.

A two-alternative forced-choice task was used. A schematic spectrogram of the stimuli for a single trial is shown in Fig. 2. There were two successive tones in each observation interval, a pure-tone probe with a duration of 1000 ms (including 20-ms raised-cosine ramps) followed after a 300-ms silent interval by a complex tone with a duration of 1000 ms (including 20-ms raised-cosine ramps). The intervals were separated by 300 ms of silence. In one randomly selected interval, the complex tone contained a series of sinusoidal partials equally spaced on the *Cam* scale. The frequency of the probe was the same as that of one of the partials in the complex. In the other interval, the probe tone was the same and the complex tone was the same, except that the partial with frequency equal to that of the probe was omitted. In the example given in Fig. 2, the partial is omitted in the second interval. The task of the subject was to indicate the interval in which a tone with a pitch corresponding to that of the isolated probe was heard in the complex tone. On a given trial, the frequencies of all components (both probe and complex) were multiplied by a factor randomly chosen from a uniform distribution between 0.9 and 1.1 (±10%). The factor varied across trials but not within a trial. The observation intervals were marked by lights on the response box, and the subject responded by pressing the appropriate button on the box. Feedback as to the correct answer was provided after each trial. The partial in the complex that was probed was selected randomly from one trial to the next. All subjects were trained until performance appeared to be stable, which took 2–3 h. Training was started using the easiest condition (component spacing of 4 *Cam*) and progressed toward the conditions with smaller *Cam* spacing.

The level per component was set to 70 dB sound pressure level (SPL), except for HI1 and the right ear of HI4, for whom this level would have been very close to the absolute

TABLE I. Frequencies of the partials in the complex tones for each spacing used (the spacing of 1.5 *Cam* was used only for HI4). The frequency of the middle partial is given in bold type.

Spacing	Frequency (Hz)										
4.0 *Cam*				375	700	**1201**	1972	3158			
3.0 *Cam*			313	520	806	**1201**	1747	2501	3547		
2.0 *Cam*		375	520	700	924	**1201**	1545	1972	2501	3158	
1.5 *Cam*	408	520	652	806	988	**1201**	1452	1747	2094	2501	2980
1.0 *Cam*	605	700	806	924	1055	**1201**	1364	1545	1747	1972	2222

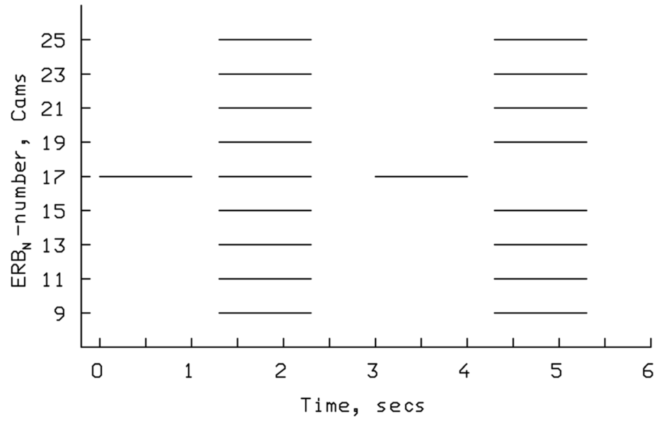

FIG. 2. Schematic spectrograms of a single trial of the procedure for measuring the ability to hear out partials.

threshold. For these two cases, the level per component was increased to 80 dB SPL. A level increase was not required for HI5, despite relatively high audiometric thresholds around 3 kHz, because the diffuse-field response of the headphones resulted in levels at the eardrum that were higher than nominal levels for frequencies around 3 kHz.

In a given block of trials, the *Cam* spacing was fixed and the probe was selected to correspond to the frequency of each partial in the complex tone five times, with the partial number selected pseudorandomly on each trial. The number of trials in a block varied from 25 (for *Cam* = 4, when the complex contained five partials) up to 55 (for *Cam* = 1, when the complex contained 11 partials). Each block was repeated ten times, so each partial in each complex was probed 50 times.

D. Stimuli and procedure for measuring F0DLs (Experiment 2)

F0DLs were measured for harmonic complex tones with a nominal F0 of 200 Hz. The tones initially contained a large number of equal-amplitude harmonics, and were passed through a fixed bandpass filter similar to that used by Moore and Moore (2003a), Moore and Moore (2003b), and Hopkins and Moore (2007). The filter had a flat central region extending from 300 to 1300 Hz, and skirts with a slope of 30 dB/octave. Thus, harmonics with numbers from 2 to 6 fell within the passband. These would be well resolved by subjects with normal hearing. They also correspond to the "dominant region" for subjects with normal hearing (Plomp, 1967; Ritsma, 1967; Moore *et al.*, 1985). The frequencies of the harmonics in the passband fell within the range of frequencies of the partials used in experiment 1. The level of each component within the passband was 70 dB SPL. The starting phases of the components were selected randomly for each tone.

A background of threshold-equalizing noise (TEN, Moore *et al.*, 2000) was used to mask combination tones and to mask components of the tones that were well outside the passband of the filter. The level of the TEN, specified as the level in a 1 *Cam* wide band around 1 kHz, was 15 dB below the level of each component.

A three-interval three-alternative forced-choice procedure was used. The F0 of the tone was 200 Hz in two of the intervals and was $200 + \Delta F$ Hz in the other (randomly selected) interval. The tone in each interval lasted 540 ms, including 20 ms raised-cosine ramps, and the intervals were separated by 200 ms of silence. The task was to select the interval containing the tone that was different from the other two tones. Note that the task did not require subjects to identify the direction of the change in F0. The observation intervals were marked by lights on the response box, and the subject responded by pressing the appropriate button on the box. Feedback as to the correct answer was provided after each trial. A trial started with a fairly large value of ΔF, chosen on the basis of pilot trials to give good performance. The value of ΔF was decreased after three successive correct responses and increased after a single incorrect response. ΔF was changed by a factor of 1.414 until four reversals had occurred and was changed by a factor of 1.189 thereafter. Testing continued until 12 reversals had occurred, and the threshold was taken as the geometric mean value of ΔF at the last eight reversals. For each test ear, ten threshold estimates were obtained, and the geometric mean of the last six was taken as the final estimate of threshold.

E. Stimuli and procedure for estimating frequency selectivity (Experiment 3)

Auditory-filter bandwidths were estimated for center frequencies of 500, 1000, and 2000 Hz, using a variant of the notched-noise method (Patterson, 1976). The signal was a tone that was pulsed repeatedly on and off (20 ms raised-cosine ramps, 160-ms steady duration, 200-ms interval between pulses). The signal level was fixed at 10 dB above the absolute threshold (10 dB SL). The background noise was presented continuously and contained a spectral notch that was centered symmetrically around the signal frequency. The overall width of the notch, expressed as a proportion of the signal frequency, was 0.0, 0.2, 0.4, and 0.6. The noise level was adjusted to determine the level required just to mask the signal.

The stimuli were prerecorded onto a compact disk. During the experiment, the stimuli were replayed via a Grason-Stadler audiometer and presented via one earpiece of Telephonics TDH50 headphones. The procedure was the same as that recommended by the British Society of Audiology (2004) for pure-tone audiometry. For each center frequency, detection thresholds were first measured for the pulsed tone in quiet, using a final step size of 2 dB. The level of the pulsed tone was then fixed at 10 dB sensation level (SL), and the level of the noise was varied to find the level (to the nearest 2 dB) at which the tone was just audible for each notch width. The masker levels at threshold for the four notch widths were used to derive the equivalent rectangular bandwidth (ERB) of the auditory filter, using the method described by Glasberg and Moore (1990). The filter was assumed to have the form of a rounded exponential (Patterson *et al.*, 1982) and was characterized by a single parameter, p (same value for the lower and upper side of the filter), that determined both the slope of the filter and its ERB. This procedure was repeated for each center frequency.

III. RESULTS

A. Experiment 1: Audibility of partials in complex tones

All subjects were able to perform the task to some extent, in that scores were well above the chance level of 50% for at least some *Cam* spacings and for some partials contained in the complexes. There was marked variability across subjects, especially for the hearing-impaired subjects. Typically, the standard deviation for a given probe frequency and *Cam* spacing was about ± 20 percentage points for the hearing-impaired subjects and ± 12 percentage points for the normal-hearing subjects, reflecting the large individual differences. However, the general *pattern* of results was broadly similar within the normal-hearing group and within the hearing-impaired group. The mean results for each group are presented in Fig. 3. Each panel shows results for one *Cam* spacing. Error bars show ± 1 standard error. The normal-hearing subjects (filled circles) performed better than the hearing-impaired subjects (open circles). The normal-hearing subjects were not tested for spacings of 3 *Cam* and 4 *Cam*, as the data obtained during training for those spacings indicated that scores were close to ceiling (100%).

For all *Cam* spacings, the results showed an asymmetric V- or U-shaped pattern. Performance was very good for the lowest partial and moderately good for the highest partial. This good performance for the "edge" partials has been found previously (Moore and Ohgushi, 1993; Moore *et al.*, 2006c) and has been attributed to the ability to determine the pitch of the edge partials from TFS information available at the outputs of auditory filters tuned below the frequency of the lowest partial and above the frequency of the highest partial. If this explanation is correct, then the fact that the hearing-impaired subjects, on average, showed better performance for the edge partials than for the inner partials suggests that they had at least some ability to use TFS information. However, the hearing-impaired subjects did perform more poorly than the normal-hearing subjects for the edge partials, especially the upper edge partial. Also, subjects HI2 and HI5 did not show any advantage for the upper edge partial.

For the hearing-impaired subjects, performance for the inner partials tended to decline with increasing frequency. For all *Cam* spacings, performance was close to the chance level of 50% for partials close to 2000 Hz. However, for *Cam* spacings of 2, 3, and 4, mean scores were mostly above chance for inner partials below 2000 Hz. Figure 4 shows scores averaged across the inner partials for each ear of the hearing-impaired subjects, plotted as a function of *Cam* spacing. Scores lying above the dashed lines are significantly above chance ($p < 0.05$), based on a binomial test. Scores for the *Cam* spacing of 1 were generally close to chance. Scores improved markedly with *Cam* spacing for some subjects (HI2, HI4L, HI4R, and HI8), but improved only slightly for other subjects (HI1, HI3, HI5, and HI6).

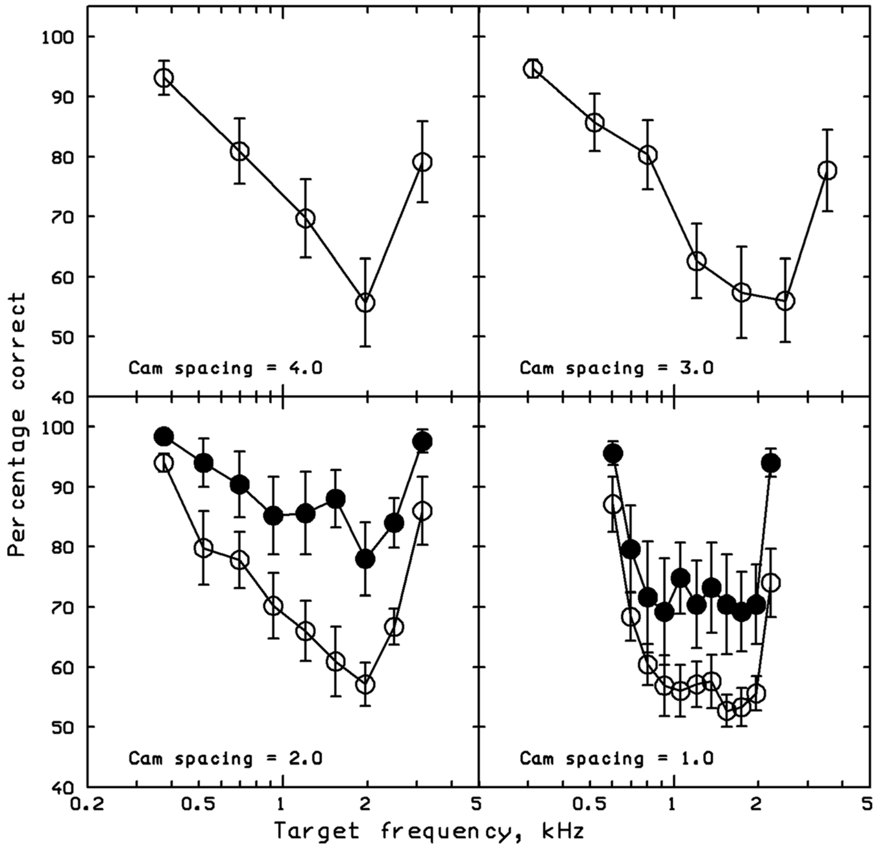

FIG. 3. The mean scores for each group (filled and open symbols denote normal and impaired hearing, respectively) for the task measuring the ability to hear out partials in complex tones. Scores are plotted as a function of the frequency of the target partial. Each panel shows results for one *Cam* spacing. Error bars show ±1 standard error.

B. Experiment 2: F0DLs

The geometric mean F0DL for the six normal-hearing subjects was 1.3 Hz (range 0.9–1.75 Hz). The F0DL for each hearing-impaired ear tested is given in Table II. There was a wide range across subjects, from 1.6 Hz for the left ear of HI4 to 17 Hz for subject HI1. Only the F0DL for the left ear of HI4 fell within the range measured for the normal-hearing subjects, confirming that hearing loss is generally associated with relatively poor F0 discrimination.

C. Experiment 3: Estimates of frequency selectivity

The ERB of the auditory filter for each hearing-impaired ear tested and each center frequency is given in Table III. ERB values are expressed as a proportion of the center frequency (ERB/CF). For example, for HI1, ERB/CF for a center frequency of 500 Hz is 0.32, so the ERB is $500 \times 0.32 = 160$ Hz. Table III also shows the root-mean-square deviation of the data from the fitted values, which is a measure of goodness of fit (Glasberg and Moore, 1990). Generally, the fits were reasonably good. The ERB/CF values varied from 0.14 (HI4, left ear at 2 kHz), a value close to normal (Glasberg and Moore, 1990; Moore, 2007; Hopkins and Moore, 2011), to 0.8 (HI6 at 2 kHz), a value about six times larger than normal.

D. Relationship between scores on the different tasks

As an overall measure of the ability to hear out partials, we calculated, for each hearing-impaired ear, the mean score for the inner partials for the spacing of 2 *Cam*. We denote this score *H*(2*Cam*). Analyses conducted with alternative summary measures yielded similar results.[1] The spacing of 2 *Cam* was chosen as most subjects scored at chance for the spacing of 1 *Cam*, and some subjects scored close to ceiling for the spacings of 3 and 4 *Cam*. Also, for the spacing of 2 *Cam*, the lowest three inner partials were spaced roughly at 200 Hz, the same as for the harmonics in the F0-discrimination task (see Table I). The correlation between *H*(2*Cam*) and the F0DL was calculated with the F0DL expressed on a logarithmic scale (as the standard deviation of each estimate of the F0DL was approximately proportional to its mean value). The resulting correlation was –0.73 ($p = 0.025$, two-tailed). Thus, a good ability to hear out partials was associated with a small F0DL. A scatter plot of *H*(2*Cam*) versus the F0DL is given in Fig. 5. The measure *H*(2*Cam*) was negatively correlated with the mean absolute threshold at 0.5, 1, and 2 kHz (covering most of the frequency range within which the inner partials fell), but the correlation was not significant ($r = –0.28$, $p = 0.46$). The F0DL was positively correlated with the mean absolute threshold at 0.5, 1, and 2 kHz, but the correlation was not significant, possibly because of the relatively small number of subjects ($r = 0.52$, $p = 0.15$).

The measure *H*(2*Cam*) was significantly negatively correlated with the average ERB/CF at 0.5, 1, and 2 kHz ($r = –0.73$, $p = 0.025$). Analyses conducted with alternative summary measures yielded similar results.[2] Thus, as expected, the ability to hear out partials was better when the

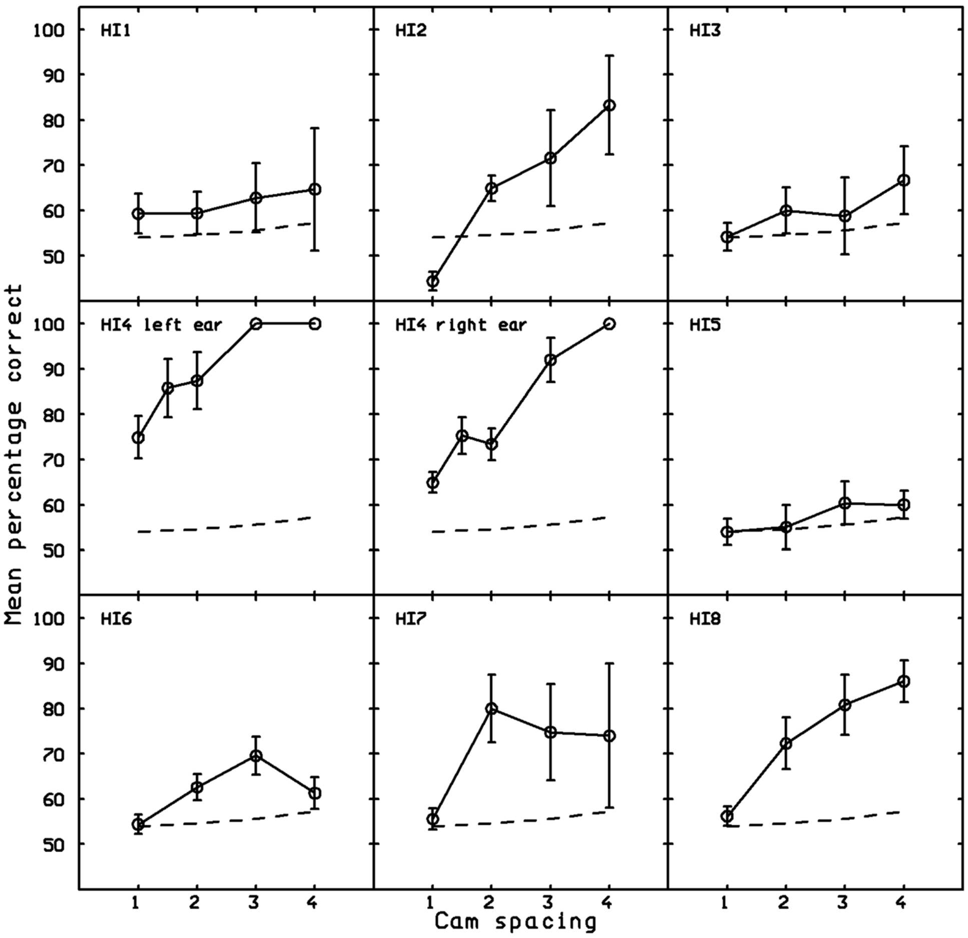

FIG. 4. Scores averaged across the inner partials for each ear of the hearing-impaired subjects, plotted as a function of *Cam* spacing. Scores lying above the dashed line are significantly above chance ($p < 0.05$) based on a binomial test.

ERB of the auditory filters was smaller. A scatter plot of $H(2Cam)$ versus the average ERB/CF is given in Fig. 6. The F0DL was also significantly positively correlated with the average ERB/CF at 0.5, 1, and 2 kHz ($r = 0.81$, $p = 0.009$). A scatter plot of the average ERB/CF versus the F0DL is given in Fig. 7. This is consistent with the findings of Bernstein and Oxenham (2006b), and with their suggestion that discrimination of the F0 of complex tones with low harmonics depends on frequency selectivity.

The ages of the subjects covered a wide range, from 26 to 84 years. It is of interest therefore to assess whether scores for any of the tasks were related to age. The measure $H(2Cam)$ was significantly negatively correlated with age ($r = -0.67$, $p = 0.047$). Thus, greater age was associated with a poorer ability to hear out partials. However, the average ERB/CF was not significantly correlated with age ($r = 0.55$, $p = 0.13$) and the F0DL was not significantly correlated with age ($r = 0.31$, $p = 0.42$).

TABLE II. The mean F0DL for each hearing-impaired ear tested. The last row shows the mean and range of the F0DL for six normal-hearing subjects.

Subject	F0DL (Hz)
HI1	16.9
HI2	2.9
HI3	14.2
HI4 (left)	1.6
HI4 (right)	2.6
HI5	7.2
HI6	7.2
HI7	2.9
HI8	11.5
NH mean	1.3 (range 0.9–1.75)

TABLE III. Estimates of ERB/CF for each hearing-impaired ear tested and for each center frequency. The root-mean-square deviation of the notched-noise data from the fitted values (in dB) is shown in parentheses (Glasberg and Moore, 1990). The bottom row shows mean ERB/CF values obtained for young subjects with normal hearing by Hopkins and Moore (2011).

	Center frequency (Hz)		
Subject	500	1000	2000
HI1	0.32 (2.0)	0.33 (0.7)	0.75 (0.6)
HI2	0.19 (1.8)	0.19 (0.7)	0.46 (1.7)
HI3	0.30 (1.4)	0.46 (0.7)	0.46 (0.7)
HI4 (left)	0.18 (0.2)	0.18 (1.0)	0.14 (1.4)
HI4 (right)	0.23 (1.0)	0.28 (0.9)	0.17 (0.5)
HI5	0.54 (1.8)	0.49 (1.8)	0.62 (0.9)
HI6	0.42 (0.5)	0.17 (1.2)	0.80 (0.5)
HI7	0.24 (1.2)	0.48 (0.9)	0.39 (2.3)
HI8	0.42 (0.5)	0.36 (0.3)	0.60 (0.8)
NH	0.17	0.17	0.15

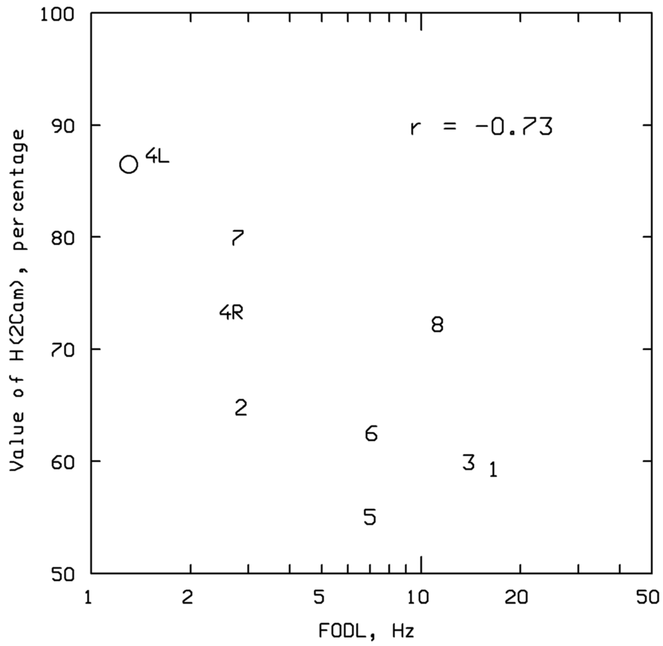

FIG. 5. A scatter plot of the value of $H(2Cam)$ versus the F0DL. $H(2Cam)$ is a measure of the ability to hear out partials in a complex tone, and represents the mean score for the inner partials for a spacing of 2 *Cam*. Numbers represent the individual hearing-impaired subjects, using the same numbers as in Fig. 1. The circle shows the mean for the six normal-hearing subjects.

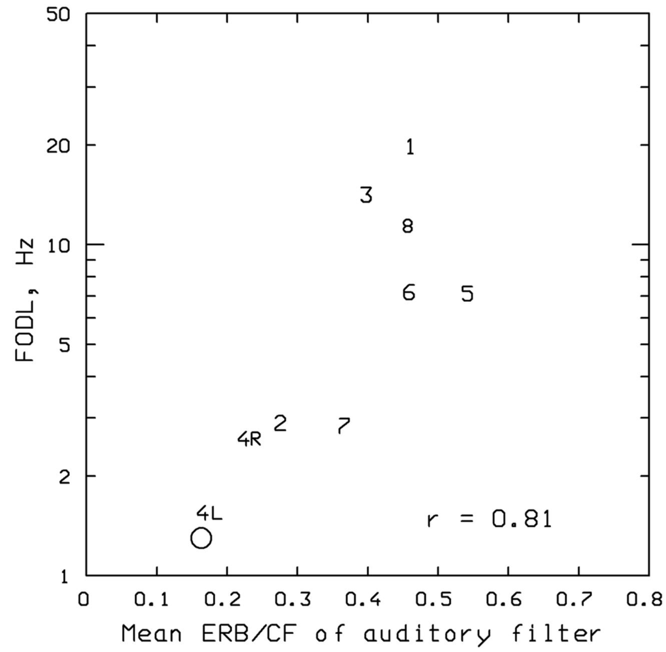

FIG. 7. A scatter plot of the F0DL versus ERB/CF averaged for center frequencies of 0.5, 1, and 2 kHz. The circle shows the mean for normal-hearing subjects [F0DL values from the present study, ERB/CF values from Hopkins and Moore (2011)].

IV. DISCUSSION

A potential ambiguity in the interpretation of the results is that, in theory, the task measuring the ability to hear out partials might be performed without actually comparing the probe to the complex tone in each interval. For example, there might be a difference in timbre between the complex tone with all components and the one with a missing component, and this might be used to perform the task. However,

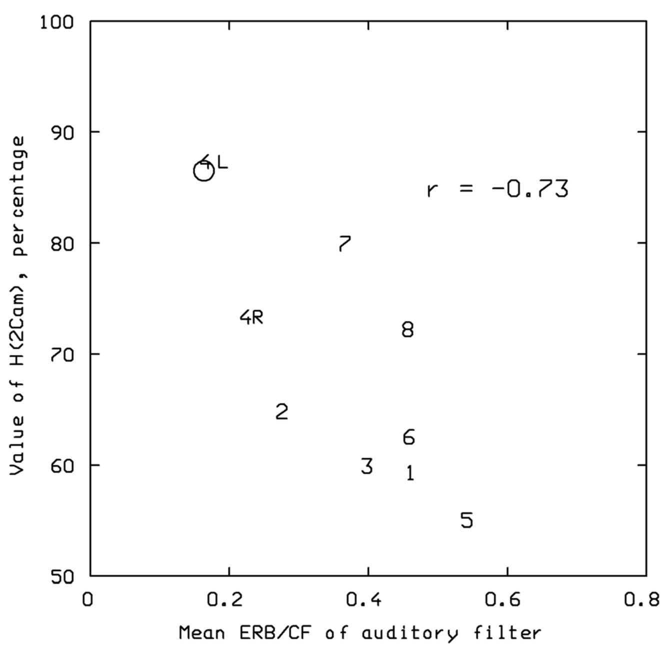

FIG. 6. A scatter plot of $H(2Cam)$ versus ERB/CF, averaged for center frequencies of 0.5, 1, and 2 kHz. The circle shows the mean for normal-hearing subjects [$H(2Cam)$ values from the present study, ERB/CF values from Hopkins and Moore (2011)].

the nature of this timbre difference would vary from trial to trial, since the partial that was probed varied randomly across trials and since the frequencies of all components (both probe and complex tone) were roved across trials. This would have made it difficult to use a timbre cue. Subjects reported that they did try to hear a pitch corresponding to the probe in the complex tone that followed each probe.

Despite the fact that the partials in the complex tones were uniformly spaced on the *Cam* scale, the ability to hear out inner partials tended to worsen with increasing frequency, for both the normal-hearing and hearing-impaired subjects. This trend has been observed previously for normal-hearing subjects, and has been attributed to a role for phase locking in the ability to hear out partials (Moore and Ohgushi, 1993; Moore *et al.*, 2006c). The trend was more marked for the hearing-impaired than for the normal-hearing subjects. To compare the effect of frequency for the normal-hearing and hearing-impaired subjects, the percent correct scores were converted to detectability index (d') values (Hacker and Ratcliff, 1979). An analysis of variance was conducted on the d' scores for the nine inner partials, with partial number as a within-subjects factor and group membership (normal hearing or hearing impaired) as a between-subjects factor. The effect of group was significant: $F(1,12) = 5.54$, $p < 0.05$. The effect of partial number was significant: $F(8,96) = 6.1$, $p < 0.001$. Importantly, there was a significant interaction between group and partial number [$F(8,96) = 10.62$, $p < 0.001$], confirming that the worsening of performance with increasing frequency was greater for the hearing-impaired than for the normal-hearing subjects. This might be partly due to the fact that audiometric thresholds and auditory-filter bandwidths, expressed as a proportion of center frequency, tended to increase with increasing frequency (see Table III). However, the more marked trend for the hearing-impaired subjects might also be partly due to reduced sensitivity to TFS at medium and high frequencies (Hopkins and Moore, 2007, 2011).

The results showed a significant correlation between the ability to hear out inner partials and frequency selectivity quantified in terms of ERB/CF, as estimated using notched-noise masking. As noted in the introduction, ERB values estimated from notched-noise masking are probably relatively independent of the use of TFS information, as similar results are obtained for very high center frequencies, above the range where phase locking is thought to occur, and for medium and low center frequencies (Shailer *et al.*, 1990; Zhou, 1995). It seems likely that the ERB values are largely determined by the filtering that takes place on the basilar membrane (Moore, 1986; Evans *et al.*, 1989). The correlation found here between ERB/CF values and the ability to hear out inner partials suggests that the ability to hear out partials is largely determined by peripheral filtering processes. However, that does not rule out a role for TFS in the ability to hear out partials (Moore and Ohgushi, 1993; Moore *et al.*, 2006c; Hartmann *et al.*, 1990; Hartmann and Doty, 1996). It is noteworthy that all of the hearing-impaired subjects scored close to chance when the frequency of the target partial was close to 2 kHz, even for the *Cam* spacings of 3 and 4. This happened even for subject HI4 who had normal or near-normal ERB values for the left and right ears at 2 kHz, and for HI8, whose ERB value was only about twice the normal value at 2 kHz. This is consistent with the idea that the ability to hear out partials depends both on peripheral filtering and on sensitivity to TFS. It may have been the case that sensitivity to TFS was largely absent at 2 kHz for our hearing-impaired subjects, because of the combined effects of the relatively high frequency and the hearing loss.

There was a significant correlation between age and the ability to hear out inner partials, as quantified by the measure $H(2Cam)$. However, age was not significantly correlated with the mean ERB/CF or the F0DL. The correlation between age and $H(2Cam)$ may have occurred because the ability to hear out partials depends partly on sensitivity to TFS, and the latter tends to decrease with increasing age (Pichora-Fuller and Schneider, 1992; Strouse *et al.*, 1998; He *et al.*, 2007; Hopkins and Moore, 2011). However, if that argument is correct, it is somewhat surprising that the F0DL was not also correlated with age. Summers and Leek (1998) also found that F0DLs for complex tones (synthetic vowels) were not significantly correlated with age for subjects with moderate to severe hearing loss. Possibly, the effects of age on the F0DL in our study and that of Summers and Leek were "swamped" by the larger effects of variations in frequency selectivity due to hearing loss. Consistent with this, Vongpaisal *et al.* (2007) measured F0DLs for a synthetic vowel using 15 younger and 15 older adults, all with normal audiometric thresholds, and found that F0DLs increased significantly with increasing age.

V. SUMMARY AND CONCLUSIONS

This study examined the relationship between the ability to hear out partials in complex tones, discrimination of the F0 of complex tones, and frequency selectivity as assessed using notched-noise masking, for subjects with mild-to-moderate cochlear hearing loss. The main goal was to assess whether the ability to discriminate changes in F0 of complex tones is correlated with the ability to hear out partials in complex tones.

The ability to hear out partials in inharmonic complex tones was measured using a new task in which subjects had to indicate which of two complex sounds contained a partial corresponding to a pure tone presented before each complex. The components in the complex tones were uniformly spaced on the ERB_N-number (*Cam*) scale, with spacings of 1, 2, 3, and 4 *Cam*. Performance was generally good for the two edge partials, but poorer for the inner partials. Performance was poorer for the hearing-impaired subjects than for a comparison group of normal-hearing subjects. Performance of the hearing-impaired subjects for the inner partials improved with increasing *Cam* spacing, especially for partials below 2 kHz. For partials with frequencies close to 2 kHz, performance was close to chance for all hearing-impaired subjects, even for $Cam = 3$ and 4.

F0 discrimination was measured for a bandpass-filtered complex tone with a nominal F0 of 200 Hz. The tone contained low harmonics and was presented in a background TEN. The threshold varied markedly across subjects from about 1.6 to 17 Hz.

The ERB of the auditory filter was estimated using the notched-noise method for center frequencies of 0.5, 1, and 2 kHz. The ERB values varied from close to normal up to about six times greater than normal.

The ability to hear out inner partials was significantly negatively correlated with the F0DL, meaning that a good ability to hear out partials was associated with good F0 discrimination. The mean value of ERB/CF across center frequencies was significantly positively correlated with the F0DL, indicating that good frequency selectivity was associated with good F0 discrimination. Finally, the ability to hear out inner partials was significantly negatively correlated with the mean value of ERB/CF across center frequencies, indicating that good frequency selectivity was associated with a good ability to hear out partials. The results are consistent with the idea that F0 discrimination of tones with low harmonics depends partly on the ability to resolve the harmonics.

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