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Frequency modulation detection in cochlear implant subjects[a)]

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Frequency modulation (FM) detection was investigated in acoustic and electric hearing to characterize cochlear-implant subjects' ability to detect dynamic frequency changes and to assess the relative contributions of temporal and spectral cues to frequency processing. Difference limens were measured for frequency upward sweeps, downward sweeps, and sinusoidal FM as a function of standard frequency and modulation rate. In electric hearing, factors including electrode position and stimulation level were also studied. Electric hearing data showed that the difference limen increased monotonically as a function of standard frequency regardless of the modulation type, the modulation rate, the electrode position, and the stimulation level. In contrast, acoustic hearing data showed that the difference limen was nearly a constant as a function of standard frequency. This difference was interpreted to mean that temporal cues are used only at low standard frequencies and at low modulation rates. At higher standard frequencies and modulation rates, the reliance on the place cue is increased, accounting for the better performance in acoustic hearing than for electric hearing with single-electrode stimulation. The present data suggest a speech processing strategy that encodes slow frequency changes using lower stimulation rates than those typically employed by contemporary cochlear-implant speech processors. *© 2004 Acoustical Society of America.*

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I. INTRODUCTION

Similar to the Fourier transform in which a signal can be decomposed into a series of sinusoids, a signal can also be decomposed into a combination of amplitude and frequency modulation components (Loughin and Tacer, 1996). Frequency modulation (FM) dynamically changes a signal's instantaneous frequency without necessarily affecting the instantaneous amplitude. The FM direction and rate, two important features that influence speech perception, are usually determined by two basic components: the carrier and the modulator. In speech and music sounds, frequency modulations in the form of formant transitions, fundamental frequency changes, and fine structure changes carry critical information for speech recognition, speaker identification, and music appreciation.

FM detection has been systematically studied in normal-hearing listeners for frequency sweeps (Sergeant and Harris, 1962; Pollack, 1968; Nabelek and Hirsh, 1969; Tsumura *et al.*, 1973; Arlinger *et al.*, 1977; Tyler *et al.*, 1983; Schouten, 1985; Dooley and Moore, 1988; Madden and Fire, 1996) and sinusoidal FM (Hartmann and Hnath, 1982; Demany and Semal, 1989; Moore and Glasberg, 1989; Edwards and Viemeister, 1994a,b; Sek and Moore, 1995; Moore and Sek, 1996). Generally, difference limens for frequency sweeps are positively proportional to the standard frequency and are relatively independent of the stimulation level. Dooley and Moore (1988) showed that the thresholds of upward and downward sweeps changed from approximately 4 Hz at standard frequency of 500 Hz to 7 Hz at a standard frequency of 1000 Hz. Previous studies were not consistent in reporting whether there is an asymmetry in detection of the downward and upward frequency glides. Schouten (1985) found that discrimination of upward sweeps required shorter durations and slower sweep rates than that of falling sweeps. Collins and Cullen (1978) reported an asymmetry in the detectability of upward and downward glides of short duration, with upward sweeps detected at lower signal intensities in the frequency ranges 200–700 Hz and 1200–1700 Hz. On the other hand, Tsumura *et al.* (1973) and Arlinger *et al.* (1977) found no significant difference between upward and downward sweeps.

Demany and Semal (1989) measured detection of sinusoidal frequency modulation as a function of carrier frequency from 250 to 4000 Hz and as a function of modulation frequency from 1 to 64 Hz. They found relatively independent effects of carrier frequency and modulation frequency on the detection threshold when the data were expressed in absolute Hz and plotted on a log scale; the difference limen increased monotonically with the carrier frequency, but remained relatively constant for different modulation frequencies. Other data suggested that the average difference limen was consistently larger when the amplitude of the frequency-modulated stimuli was either sinusoidally or randomly modulated (Grant, 1987).

Two theories have been put forward to explain the frequency coding mechanism. One theory relies on the ''place code'' in the cochlea (Zwicker, 1956; Henning, 1967) while

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TABLE I. Subject information of three Nucleus-22 cochlear-implant users who participated in this study.

Subject	Gender	Age (years)	Cause of deafness	Duration of implant use (years)	Vowel recognition	Consonant recognition
S1	F	69	Cochlear otosclerosis	13	69%	69%
S2	M	59	Hereditary	6	59%	72%
S3	M	45	Trauma	10	71%	79%

the other uses the ‘‘temporal code’’ or ‘‘phase locking code’’ in the auditory nerve (Siebert, 1970; Goldstein and Srulovicz, 1977). In the place theory, the cochlea is modeled as a bank of filters and the cochlear filters’ response is called an excitation pattern. When the stimulus frequency is changed, the filters’ output is changed systematically dependent upon the filters’ bandwidth and slope. Based on this theory, a common mechanism is used for processing both frequency discrimination and frequency modulation. However, Moore and Glasberg (1989) compared the difference limen between pulsed sinusoids and frequency modulations. The data showed that difference limens of pulsed sinusoids (DLFs) varied more with frequency than did the difference limens of frequency modulation (FMDLs). In addition, DLFs were less affected by the random variation in level and by the addition of bandpass noise than the FMDLs. These data were not consistent with the prediction of the excitation model, which posits that different mechanisms are involved in frequency discrimination and frequency modulation detection. Different from the place code, a temporal code extracts frequency changes from the temporal firing patterns of the nerve fibers that innervate the same cochlear place (Rose *et al.*, 1967). There is a body of evidence for a temporally based mechanism in FM detection, particularly at low-modulation rates (e.g., <20 Hz) and in hearing-impaired listeners (Edwards and Viemeister, 1994a; Moore and Sek, 1995, 1996). However, phase locking to sinusoids only occurs at frequencies lower than 4000–5000 Hz in the mammalian auditory nerve (Palmer and Russell, 1986), and it is unlikely that temporal cues can encode FM at high frequencies.

In acoustic hearing, one of the critical issues has been to reduce the interaction between ‘‘temporal coding’’ and ‘‘place coding’’ so that the two mechanisms can be studied separately. Electric stimulation of the auditory nerve provides a unique opportunity to address the relative contributions of the place and temporal mechanisms to frequency coding. For frequency discrimination tasks, the electric stimulation rate can be varied and delivered to the same electrode, presumably producing a change in the firing rate of the auditory nerve without any change in the excitation place. Under these conditions, electrical rate discrimination tasks have shown that some cochlear-implant users can detect pitch differences only up to 300–500 Hz (Bilger, 1977; Eddington *et al.*, 1978; Simmons *et al.*, 1981; Shannon, 1983; Fearn *et al.*, 1999; Zeng, 2002) while others show that pitch saturates at about 1000 Hz (Hochmair-Desoyer *et al.*, 1983; Townshend *et al.*, 1987). These data have been interpreted as an indication of the 500–1000-Hz upper limit for purely temporally based mechanism for pitch encoding. To our knowledge, there is only one study in the literature that has measured FM detection in cochlear-implant users (Tong *et al.*, 1982). The difference limen was about 10% of the standard frequency for a 100-Hz carrier with 10-Hz modulation frequency in two cochlear-implant users. In general, studies in electric hearing indicate that temporal cues might play a role in frequency discrimination and FM detection at low frequencies.

To further investigate the mechanism underlying dynamic frequency encoding, the present study systematically measured FM detection in cochlear-implant subjects. The goals of this study were twofold. One goal was to characterize cochlear-implant users’ ability to detect frequency modulation. This goal was driven by a need in applications. Contemporary cochlear implants typically extract the temporal envelope but discard the temporal fine structure in the acoustic stimulus. The temporal envelope is typically used to amplitude modulate a fixed-rate carrier, which clearly does not reflect the natural way by which the acoustic information is transmitted to the brain via the auditory nerve. This study hopes to provide psychophysical evidence for using FM to convey additional speech and music information (Nie *et al.*, 2004b). The second goal, which has a more theoretical underpinning, was to use the electric hearing data to help delineate the mechanisms underlying FM detection in acoustic hearing.

II. METHODS

A. Subjects

Three post-lingually deafened adults with Nucleus-22 cochlear implants participated in this study. The subjects ranged in age from 45 to 69 years with a mean age of 58 years and were all native speakers of American English. All subjects had 6 or more years of experience with the device and consonant recognition scores of at least 69% correct. They also had extensive previous experience in psychophysical and speech tests. Detailed subject information is presented in Table I.

Three normal-hearing subjects also participated in this study. Their ages ranged from 20 to 25 years with a mean age of 23 years. None of the normal-hearing subjects had prior experience in psychophysical tests. They gave informed consent and were paid for their participation.

B. Stimuli

Three types of frequency modulation, upward sweep, downward sweep, and sinusoidal frequency modulation, were used in the experiment. For the upward sweep and downward sweep, the electric stimulation parameters studied were electrode position (apical versus basal), stimulation level (most comfortable level versus soft level), and different standard frequencies. Loudness was measured using unmodulated stimuli at each standard frequency. The subjects first received subthreshold stimulation and then had to indicate when the soft and the most comfortable levels (MCL) were reached with gradually increasing current level. The MCL was 65%–70% of the maximum loudness level that subjects could tolerate, while the soft level was 25%–30% of the maximum loudness level. An additional parameter studied was the FM rate for the sinusoidal FM pattern. To avoid aliasing, the modulation rate was set at least 40% less than the standard frequency, being systematically varied from 5 to 320 Hz at the 1000-Hz standard frequency, from 5 to 160 Hz at 500 Hz, from 5 to 80 Hz at 250 Hz, from 5 to 40 Hz at 125 Hz, and from 5 to 10 Hz at 75 Hz. All stimuli were represented as 300-ms trains of biphasic pulses and were presented to a single, bipolar electrode pair in BP+1 mode (1.5-mm spacing between the active and reference electrodes). The phase duration and temporal separation between opposite phases of each pulse were 200 and 20 μs, respectively. The electric stimuli were delivered to the subject and controlled via a customized research interface[1] (Shannon *et al.*, 1990).

Figure 1 shows three types of FM stimuli in the frequency-time domain. The standard is represented by the solid line while the signal is represented by the dotted line. The parameter to be measured is the frequency difference between the signal and the standard at the end for the upward sweep, at the beginning for the downward sweep, and modulation depth for the sinusoidal FM stimuli.

To minimize the loudness cue due to the change in the stimulation rate, the instantaneous amplitude of each pulse in the electric stimuli was roved by a value that was uniformly distributed between -1 and 0 dB. Amplitude roving was applied to both standard and FM stimuli, so that levels of all three stimuli in each trial were randomized. Although 1 dB may be small, it corresponds to 10–20 dB roving in acoustic hearing because current cochlear-implant users typically have a narrow dynamic range of 10–20 dB (e.g., see Zeng and Galvin, 1999; Zeng *et al.*, 2002). Zeng and Shannon (1999) reported essentially no loudness change as a function of pulse rate from 100 to 3000 Hz in six cochlear-implant users. For example, the maximum difference in current levels producing equal loudness was only 0.40 dB between 1000 to 2000 Hz. With 30% or less frequency modulation and 1-dB roving in this study, loudness was unlikely to be a confounding cue.

In acoustic stimulation for the normal-hearing subjects, the carrier was a sinusoid generated using TDT System III equipment (RP2.1) and presented at 65 dB SPL monaurally via Sennheiser headphones (200A). Neither level roving nor background noise was used. Moore and Glasberg (1989) showed a nonsignificant effect of level randomization on FM detection in normal-hearing listeners with a relatively small range of level variations (3 dB). Emmerich *et al.* (1989) suggested that level randomization with a large range of variations could produce pitch shift with level, providing subjects with additional cues in frequency discrimination.

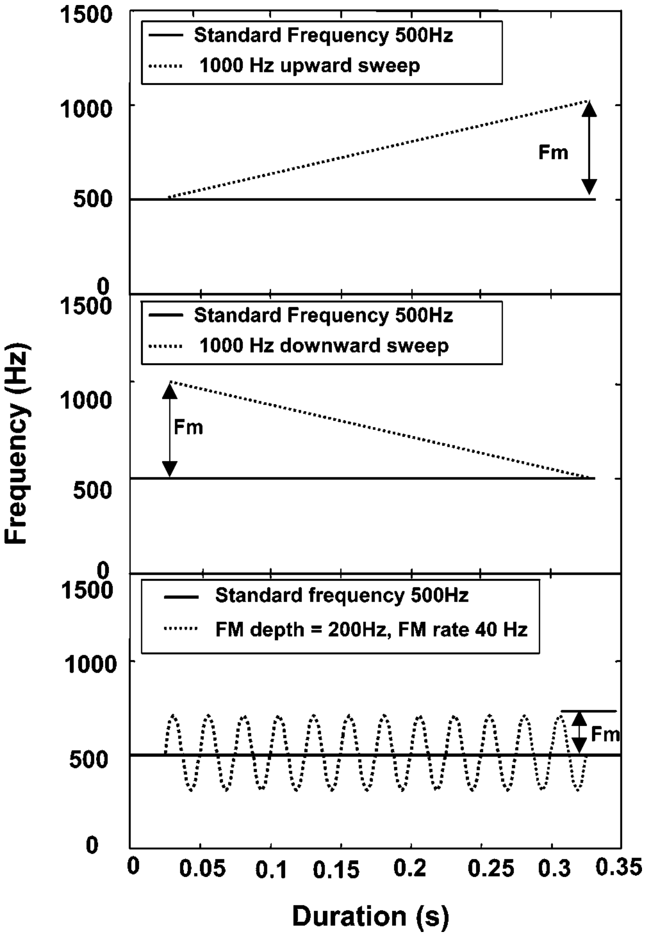

FIG. 1. Three patterns of frequency modulation examined in the present study: upward sweep (top panel), downward sweep (middle panel), and sinusoidal frequency modulation (bottom panel).

C. Procedures

FM difference limens were measured using a three-interval, forced-choice, adaptive procedure. A three-down, one-up decision rule was employed to track the 79.4% percent correct point on the psychometric function. In each trial, a subject heard three sounds including two steady-frequency standard signals and one frequency-modulated signal. The order of presentation was randomized. The subject was asked to identify the interval with the greatest change in pitch by pressing a button on a computer monitor. Visual feedback was given after each trial. The run terminated after 13 reversals or 60 trials with at least eight reversals. The step size was about 25% of the standard frequency for the first four reversals and reduced to 3%–5% thereafter. The difference limen was averaged over the last eight reversals. All subjects completed at least three successful runs with an average standard deviation of about 50% of the mean value.

III. RESULTS

A. Frequency sweep

Figure 2 shows frequency sweep difference limens in Hertz (Hz) as a function of standard frequency for the up-

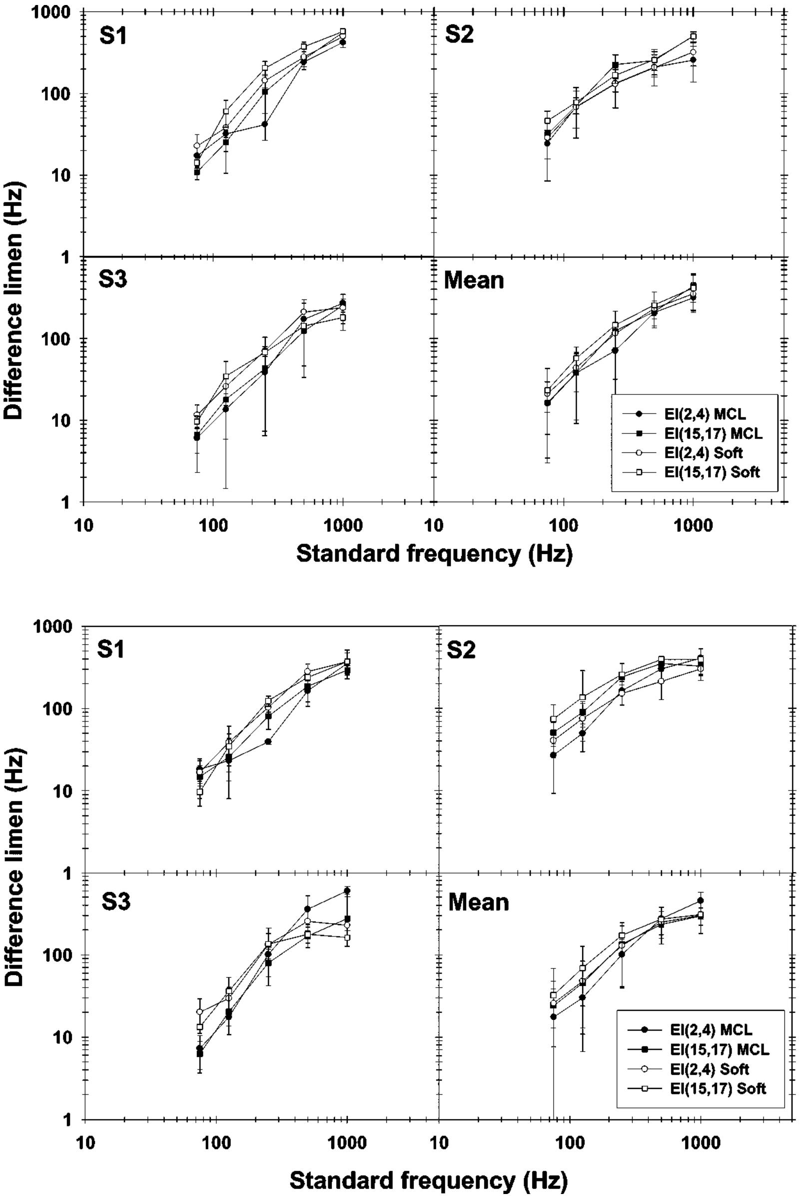

FIG. 2. Difference limens for frequency sweeps in three cochlear-implant subjects. The upper panel represents the data from the upward sweep and the lower panel represents the data from the downward sweep. Each graph shows the data for a single subject or the mean data (bottom-right graph in each panel). The *x* axis is the standard frequency and the *y* axis is frequency modulation difference limen. Circles represent the data collected from the basal electrode while squares represent the data collected from the apical electrode. The open symbols represent the data at the soft level while the filled symbols represent data at MCL.

ward sweep (upper four panels) and the downward sweep (lower four panels). The individual data are represented according to the subject number (S#) and the mean data are shown in the bottom-right panel. The data from the apical electrodes are represented by squares while those from the basal electrodes are represented by circles. The data for the MCL are represented by filled symbols while those from the soft level are represented by open symbols.

In general, the difference limen is proportional to the standard frequency regardless of the sweep type, electrode position, and loudness level. A four-way ANOVA with a within-subject design and repeated measures confirms a significant main effect for the standard frequency $[F(4,8)=36.4,\ p<0.01]$ but not for the other variables $(p>0.05)$. To compare the FM sweep detection between acoustic and electric hearing, Fig. 3 shows the grand averaged data across all conditions in cochlear-implant subjects (filled circles) as well as the acoustic data averaged over the upward and downward sweep types from three normal-hearing subjects (open circles).[2] The grand averaged difference limen in electric hearing ranged from 22 Hz at 75-Hz standard frequency to 361 Hz at 1000-Hz standard frequency, corresponding to Weber fractions (the ratio of difference limen to the standard frequency) of 0.29 and 0.36, respectively.

In contrast to the rising function in electric hearing, normal-hearing listeners show a relatively flat function with a much smaller difference limen between 5 and 10 Hz at all standard frequencies tested. Except for the lowest standard frequency (75 Hz), there is no overlap in the difference limen functions between acoustic and electric data. The higher the standard frequency, the poorer the performance in electric hearing as compared to acoustic hearing.

B. Sinusoidal frequency modulation

Figure 4 shows the individual and mean difference limens for sinusoidal FM as a function of standard frequency in cochlear-implant subjects. Since neither stimulation level nor electrode site produced any significant effects, the data were averaged over both levels and electrodes.

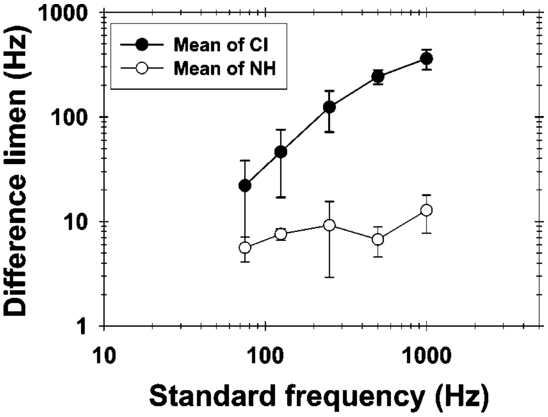

FIG. 3. The mean of difference limens for frequency sweeps for both normal-hearing (filled circles) and cochlear-implant subjects (open circles). Error bars represent plus and minus one standard error.

The obtained data were analyzed in two ways to deal with the missing data at higher modulation rates. First, the data from modulation rates at 5, 10, and 20 Hz were examined using a within-subject design and a four-way repeated-measures ANOVA (stimulation level×electrode×standard frequency×FM rate). Similar to the FM sweep result, standard frequency was the only significant main factor: the difference limen increased monotonically from about 10 Hz at the 75-Hz standard to about 100 Hz at the 1000-Hz standard $[F(4,8)=21.4,\ p<0.05]$. Second, a three-way ANOVA was used to examine the main effects of electrode, loudness, and modulation rate at different standard frequencies. No significant main effect was found except for the greater difference limen at higher modulation rates than at the lower modulation rates. The difference limen was 294.3 Hz for the 160-Hz modulation rate at the 500-Hz standard $[F(5,10)=12.0,\ p<0.05]$, 400.0 and 549.4 Hz for the 160- and 320-Hz rates at the 1000-Hz standard $[F(6,6)=14.4,\ p<0.05]$, respectively.

To facilitate comparison, the averaged data from three normal-hearing listeners are shown on the bottom-right panel of Fig. 4. Again, in contrast to the cochlear-implant data, the averaged normal-hearing data show a relatively flat function with no significant effects of either standard frequency or modulation rate $(p>0.05)$. If anything, there was a trend for higher modulation rates (160 and 320 Hz) to produce smaller difference limens than the lower modulation rates $[F(2,4)=9.6,\ p=0.06]$.

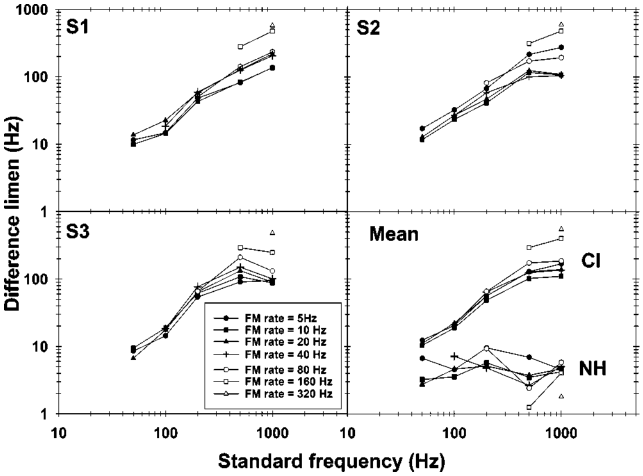

FIG. 4. Difference limens of sinusoidal frequency modulation in three cochlear-implant subjects. The bottom-right panel represents the mean value in both cochlear-implant (CI) and normal-hearing (NH) subjects. Different symbols represent different modulation rates.

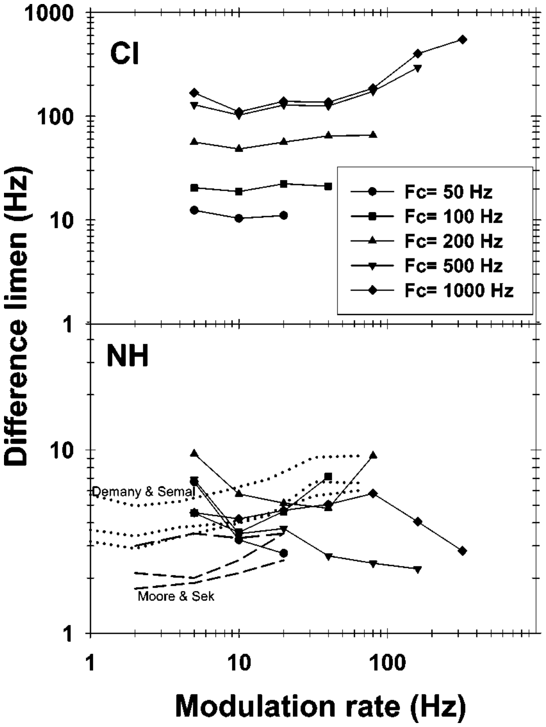

FIG. 5. Comparison of difference limens between normal-hearing and cochlear-implant subjects for sinusoidal frequency modulation. Difference limens are plotted as a function of modulation rate. Different symbols represent different standard frequencies from 50 to 1000 Hz. Previous data from Demany and Semal (1989) are presented as three dotted lines and those from Moore and Sek (1996) are presented as three dashed lines. Each of the three lines represents a different standard frequency (1000, 500, and 250 Hz for lines from top to bottom, respectively).

IV. DISCUSSION

A. Comparison with previous studies

Figure 5 replots the sinusoidal FM data (Fig. 4) as a function of modulation rate in cochlear-implant subjects (upper panel) and compares the difference limens between the present and previous studies in normal-hearing subjects (lower panel). Previous data from Demany and Semal (1989) are presented as three dotted lines and those from Moore and Sek (1996) are presented as three dashed lines. Each of the three lines represents a different standard frequency (1000, 500, and 250 Hz for lines from top to bottom, respectively). Different standard frequencies are represented by different symbols in the present study.

Given that only three cochlear-implant subjects were tested and all were good users, the current data may not represent the performance of the broader cochlear-implant population. However, several general trends could be gleaned from the limited data. First, for standard frequencies of 200 Hz and higher, the difference limen for sinusoidal FM is one to two orders of magnitude poorer in electric hearing than acoustic hearing. Second, the difference limen mono-

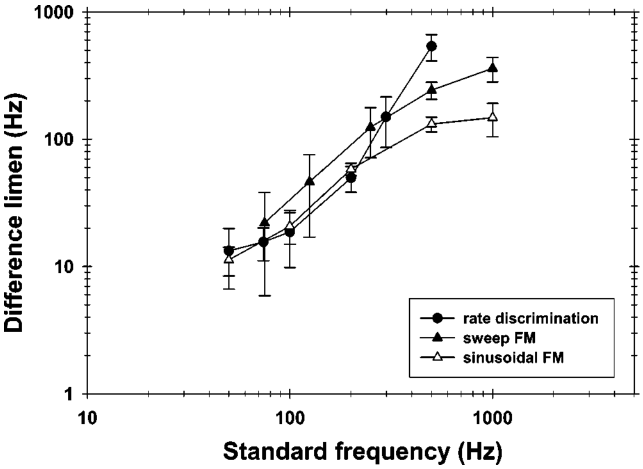

FIG. 6. Comparison of difference limens between rate discrimination (filled circles), frequency sweep (filled triangles), and sinusoidal frequency modulation (unfilled triangles) in cochlear-implant subjects. The data for the frequency sweep represent the average of both sweep types, levels, electrodes, and all subjects. The data for the sinusoidal frequency modulation represent the average across levels electrodes modulation rates, and subjects. The data for the rate discrimination represent the average of four subjects on both electrodes from a previous study (Zeng, 2002).

tonically increases with the standard frequency in electric hearing. In acoustic hearing, although the present data are in the same range as the previous data, this monotonic relationship is not as orderly as it was in the previous data. One possible reason is that relatively high ratios of modulation rates to standard frequencies were used in the current study and this may have allowed subjects to rely more strongly on place cues to differentiate the stimuli. Third, the difference limen is relatively independent of the modulation rate in both acoustic and electric hearing, with the difference limen showing an increasing trend at the highest modulation rates (160 and 320 Hz) in electric hearing and a decreasing trend at these rates in acoustic hearing.

Because only the temporal cue is available to cochlear-implant subjects, we interpret the present result as providing evidence for a significant role of the place cue in FM detection for normal-hearing listeners. The difference limens between acoustic and electric hearing are close in value only at low standard frequencies. As the standard frequency increases, FM difference limens in cochlear-implant users are elevated significantly. The opposing trend at high modulation rates (160 and 320 Hz) between acoustic and electric hearing further suggests that the temporal cue is most effective at low modulation rates ($<$80 Hz). Together, these data suggest that the temporal mechanism operates only for low standard frequencies at low modulation rates.

Figure 6 compares cochlear-implant subjects' pulse-rate difference limens from a previous study [filled circles; from Zeng (2002)] with difference limens for sinusoidal (unfilled triangles) and sweep (filled triangles) FM in the present study. The data represent a grand average across subjects, levels, and electrodes. Data could not be collected for rate discrimination at 1000 Hz as subjects reported no pitch difference between stimuli. Difference limens were generally similar for standard frequencies less than 300 Hz for all three tasks, but diverged at higher standard frequencies. Cochlear-implant subjects typically could not detect a pitch difference based on rate above 300–500 Hz, but appeared to be able to detect FM differences, with sinusoidal modulation producing the smallest difference limens at these high frequencies. The ability to detect sinusoidal frequency modulation with high carrier frequency and low modulation rate may be related to previously observed temporal pitch changes between the pitch of the carrier and the pitch of the modulator in sinusoidal amplitude modulations (McKay *et al.*, 1995; McKay and Carlyon, 1999). Further study is needed to determine whether FM and AM related pitch changes in electric hearing have the same underlying mechanisms.

There are at least two reasons that sinusoidal FM produced the smallest difference limen. First, for a constant difference limen, the frequency-varying rate in sinusoidal FM is greater than that in frequency sweeps. For instance, the difference limen of 229 Hz at 500 Hz for a 300-ms upward sweep would produce a frequency-varying rate of 763 Hz per second ($\Delta F/\Delta t = 229\,\text{Hz}/0.3\,\text{s} = 763\,\text{Hz/s}$). On the other hand, the difference limen was 129 Hz for the 300-ms sinusoidal FM with 500-Hz standard frequency and 5-Hz modulation rate. The frequency-varying rate in one cycle can be approximated by the peak-to-valley frequency difference divided by half of the period, equaling to $\Delta F/\Delta t = 129/0.1 = 1290\,\text{Hz/s}$. Second, the sinusoidal FM can be viewed as a series of frequency downward and upward sweeps (see Fig. 1). It is possible that ''multiple looks'' (Viemeister and Wakefield, 1991) at frequency changes produced smaller difference limens for sinusoidal FM than the ''single look'' for frequency sweeps.

B. Mechanisms

The present results may shed light on two unresolved issues in dynamic frequency encoding. One issue is the relative contributions of spectral and temporal cues to FM processing. The spectrum of sinusoidally frequency-modulated signal consists of the carrier frequency plus and minus all the integer multiples of the modulation rate (Chowning, 1973). At low modulation rates (5–80 Hz), a listener can process temporally varying pitch by following changes in instantaneous frequencies. This mechanism is primarily temporally based, as evidenced by the relatively close values in difference limens at these low modulation rates between acoustic and electric hearing. At higher modulation rates, FM detection is likely to be performed by detecting the timbre change induced by the additional sidebands. This is a spectrally based mechanism, requiring the ear to resolve sidebands in the frequency domain. Cochlear-implant subjects cannot perform this task via single-electrode stimulation, thus producing increasingly poorer performance at higher modulation rates.

The other issue is whether amplitude and frequency modulations are processed independently by the auditory system (Moore and Sek, 1992; Edwards and Viemeister, 1994b; Saberi and Hafter, 1995). This controversy has been difficult to resolve because amplitude modulation and frequency modulation interact at the excitation pattern level in acoustic hearing (Zwicker, 1952). A ''pitch-sampling model'' has been proposed to explain the FM processing, in which

FM detection is based upon successive samplings of a stimulus's pitch using a relatively short-term temporal window (Hartmann and Klein, 1980; Demany and Semal, 1986). Edwards and Viemeister (1994b) compared the discriminability of equally detectable amplitude- and frequency-modulated signals and suggested a second frequency-modulation encoding mechanism that tracks the instantaneous frequency. The present study provides direct evidence for such a mechanism given that cochlear-implant subjects cannot resolve the sidebands in frequency modulations. The present study also extends the boundary that such a temporally based cue may be available from 10 Hz or below to at least 80 and possibly 320 Hz (Moore and Sek, 1995, 1996). Because FM difference limens at these modulation frequencies are always poorer in electric hearing than in acoustic hearing, the temporal coding of FM is considered ''sluggish.''

Finally, inconsistent with the Schouten (1985) study, the present result shows no perceptual imbalance between upward and downward sweeps. This inconsistency may be explained by the findings of Kohlrausch and Sander (1995) and Carlyon and Datta (1997) that asymmetry in frequency modulation is due to the cochlear nonlinearity. In their studies, a complex tone with positive or negative Schroeder phase was used to mask a sinusoidal tone, and the result showed that the positive Schroeder-phase stimulus (downward sweep) produced much less masking than the negative Schroeder-phase stimulus (upward sweep). Interestingly, recent studies (Recio and Rhode, 2000; Summers *et al.*, 2003) presented direct evidence that the nonlinear cochlear filter produces more amplitude modulation with the positive Schroeder-phase stimulus than the negative Schroeder-phase stimulus, pointing again to a possible common mechanism between amplitude and frequency modulation. In cochlear-implant subjects, the cochlear nonlinearity is totally absent, producing no difference in FM detection between downward and upward sweeps.

C. Clinical application

The present result may also help improve speech-processing strategies for cochlear-implant subjects. Most contemporary cochlear implants have employed a fix-rate carrier strategy (Wilson *et al.*, 1991; McDermott *et al.*, 1992) and are continuing to increase the carrier rate in order to better represent the temporal envelopes and/or to restore stochastic responses in electrically stimulated auditory nerve fibers (Rubinstein *et al.*, 1999). The present study suggests that cochlear-implant subjects can benefit from a new speech processing strategy, in which, instead of using a constant, high-rate carrier, the carrier rate may be changed dynamically on each electrode according to the frequency change in the input acoustic signal (Lan *et al.*, 2004; Nie *et al.*, 2004b). The present result clearly demonstrates that cochlear-implant subjects can access the FM information at least for standard frequencies up to 1000 Hz and modulation rates up to 320 Hz. The encoding of frequency modulation with relatively lower pulse rates, in combination with amplitude modulation, could provide information regarding both the temporal fine structure and envelope in speech and music. Such a strategy may have the potential to improve pitch perception and other pitch related tasks including speaker identification, auditory object segregation, and tonal language perception (Xu and Pfingst, 2003; Kong *et al.*, 2004; Nie *et al.*, 2004a).

V. CONCLUSIONS

FM detection was assessed for upward frequency sweeps, downward frequency sweeps, and sinusoidal FM in three cochlear-implant and three normal-hearing subjects. The following conclusions could be made:

(1) Regardless of the FM type, the FM difference limen increased monotonically as a function of standard frequency in electric hearing. On the contrary, the difference limen was nearly constant as a function of standard frequency in acoustic hearing. Only at low standard frequencies (75 Hz) did the difference limen in electric hearing approach that in acoustic hearing. At high standard frequencies, the difference limen in electric hearing was one to two orders of magnitude larger than that in acoustic hearing.

(2) There was no significant difference in difference limens between upward and downward sweeps. Neither stimulation level nor electrode position was a significant factor in FM detection in electric hearing.

(3) The difference limen for sinusoidal FM detection was not significantly affected by modulation rate except at 160 and 320 Hz for detecting sinusoidal FM in electric hearing.

(4) The present result supports the existence of an independent temporally based FM coding mechanism, particularly at low standard frequencies and at low modulation rates.

(5) The present finding suggests that FM via varying pulse rate may be used to encode the temporal fine structure in cochlear implants to improve their performance in pitch perception and other pitch-related tasks such as speaker identification, auditory object segregation, and tonal language perception.

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[1] J. Wygonski and M. E. Robert, ''HEI Nucleus research interface specification,'' House Ear Institute (2001).

[2] No statistical significant difference was observed between the upward and downward sweeps in normal-hearing subjects $[F(1,2)=1.7,\ p>0.05]$.

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