Published in final edited form as:

J Acoust Soc Am. 2008 April ; 123(4): 2276–2286. doi:10.1121/1.2874796.

Pulse-rate discrimination by cochlear-implant and normal-hearing listeners with and without binaural cues

Robert P. Carlyon^a, Christopher J. Long, and John M. Deeks

MRC Cognition & Brain Sciences Unit, 15 Chaucer Rd., Cambridge CB2 7EF, England

Abstract

Experiment 1 measured rate discrimination of electric pulse trains by bilateral cochlear implant (CI) users, for standard rates of 100, 200, and 300 pps. In the diotic condition the pulses were presented simultaneously to the two ears. Consistent with previous results with unilateral stimulation, performance deteriorated at higher standard rates. In the signal interval of each trial in the dichotic condition, the standard rate was presented to the left ear and the (higher) signal rate was presented to the right ear; the non-signal intervals were the same as in the diotic condition. Performance in the dichotic condition was better for some listeners than in the diotic condition for standard rates of 100 and 200 pps, but not at 300 pps. It is concluded that the deterioration in rate discrimination observed for CI users at high rates cannot be alleviated by the introduction of a binaural cue, and is unlikely to be limited solely by central pitch processes. Experiment 2 performed an analogous experiment in which 300-pps acoustic pulse trains were bandpass filtered (3900–5400 Hz) and presented in a noise background to normal-hearing listeners. Unlike the results of experiment 1, performance was superior in the dichotic than in the diotic condition.

I. INTRODUCTION

An important finding in the cochlear-implant (“CI”) literature concerns a limitation in CI users' sensitivity to changes in the rate of a train of pulses applied to a single channel of their device. At low rates, most listeners can detect rate changes, with average difference limens (DLs) of about 7% (Moore and Carlyon, 2005), and some listeners can make musical judgements, such as the identification of melodies and the production and identification of musical intervals (Pijl and Schwarz, 1995; McDermott and McKay, 1997). However, once the rate exceeds about 300 pps, performance for the majority of CI users deteriorates markedly (Shannon, 1983; Tong and Clark, 1985; Townshend et al., 1987; McKay et al., 2000). The finding has both theoretical and practical implications. In terms of theory, it provides insights into the limitations of pitch perception in the absence of place-of-excitation cues (so-called “purely temporal” pitch perception: Carlyon et al., 2002; Carlyon et al., 2007). In practical terms, a number of authors have suggested novel speech-processing schemes that present temporal fine structure to CI electrodes (Nie et al., 2005; Stickney et al., 2005; Stickney et al., 2007). It seems likely that the success of those schemes will be constrained by the sensitivity of CI users to fast timing differences. The poor rate discrimination above 300 pps strongly suggests that this sensitivity may be limited or absent, and so it seems worthwhile to study the nature of that limitation.

In a previous article (Carlyon and Deeks, 2002), we studied the limitations on rate discrimination in normal-hearing (“NH”) listeners, using acoustic pulse trains that had been

Corresponding author: Robert Carlyon, Tel +44 1223 273717, Fax: +44 1223 359062.

^aElectronic mail: bob.carlyon@mrc-cbu.cam.ac.uk

PACS numbers: 43.66Hg, 43.66Ts, 43.64Pg

bandpass filtered so that, in many conditions, harmonics that were resolved by the peripheral auditory filters were removed. A number of other studies have shown that the results obtained with such pulse trains mimic those observed when analogous electric pulse trains are presented to one channel of a CI (McKay and Carlyon, 1999; Carlyon et al., 2002; van Wieringen et al., 2003; Carlyon et al., 2007). Carlyon and Deeks reported a number of findings that shed light on the limitations of temporal pitch perception: (i) Like CI users, NH listeners also showed an “upper limit” for rate discrimination, (ii) That limit increased as the sounds were filtered into higher frequency regions in a way that could not be attributed to the effects of peripheral filtering in the auditory system, (iii) in the highest frequency region tested (7800-10800 Hz), the limit was 600 pps – substantially higher than that observed for most CI listeners, (iv) for a 600-pps pulse train filtered between 3900-5400 Hz, where performance with monotic presentation was at chance, discrimination could be substantially improved by the presentation of another pulse train to the contralateral ear in each interval of a forced-choice trial. The contralateral pulse train was always the same as the lower of the two possible rates presented ipsilaterally, so that the standard (lower-rate) intervals consisted of a diotic pulse train, whereas in the signal interval the stimuli in the two ears differed slightly. This provided a binaural cue, which was the presumed basis of the improvement in performance. This last experiment was inspired by a similar manipulation applied to electric pulse trains having rates between 50 and 200 pps in two CI listeners by van Hoesel and Clark (van Hoesel and Clark, 1997). They also observed that, at least at rates below 100 pps, the contralateral stimulus improved performance.

Carlyon & Deeks' (2002) observation that rate discrimination of high-rate pulse trains could be improved by introducing a binaural cue led them to conclude that, for NH listeners, the mechanisms underlying the upper limit of rate discrimination included a component that was specific to the pitch mechanism. In particular, they argued that, as performance was no longer at chance when a binaural cue was introduced, some information on the timing of the individual pulses must have been present at the level of the auditory nerve (“AN”). However, as they pointed out, this does not necessarily apply to CI users: the fact that the upper limit of 600pps observed for NH listeners was higher than the 300 pps observed for most CI listeners suggested that the latter group may have an additional, peripheral limitation to rate discrimination at high rates. Some evidence in support of this interpretation comes from the fact that the discrimination of interaural time differences (ITDs) between equal-rate pulse trains deteriorates with increases in pulse rate (van Hoesel and Tyler, 2003; Majdak et al., 2006; van Hoesel, 2007). The present study therefore measured rate discrimination with and without binaural cues in four bilateral CI users, for pulse rates between 100 and 300 pps. The aim was to determine whether, for pulse rates sufficiently high for monotic or diotic rate discrimination to deteriorate, there was sufficient information at the level of the AN for performance to improve when a binaural cue was added. This first experiment was similar to, but differed in several ways from, a recent study by van Hoesel (2007), which was published during the preparation of this article¹. A comparison of the methods, results, and conclusions from experiment 1 with those of van Hoesel will be provided in the following sections.

To allow a more direct comparison with the limitations on rate discrimination observed with acoustic stimulation of the normal auditory system, experiment 2 studied rate discrimination in the presence and absence of binaural cues in five NH listeners. That experiment used similar procedures and conditions to experiment 1, and used acoustic pulse trains that had been bandpass filtered to remove resolved harmonics. Experiment 2 differed from most previous acoustic studies in that it compared sensitivity to monaural rate differences with

¹Preliminary data from experiment 1 and from the study by van Hoesel (2007) were also presented at the 2003 Conference on Implantable Auditory Prostheses, held at Asilomar, Pacific Grove, California.

that to a time-varying decorrelation, using stimuli that, we have argued, are directly analogous to those employed with CI users (McKay and Carlyon, 1999; Carlyon et al., 2002; van Wieringen et al., 2003).

II. EXPERIMENT 1: CI USERS

A. Method

1. Listeners—Four bilaterally implanted users of the Nucleus CI 24M cochlear implant took part. They had been without binaural hearing prior to their second CI for between 8 and 13 years (Table I), and were the same listeners as had taken part in the study by Long et al (2006b). The electrode pairs tested in each ear were also the same as used by Long *et al*. They were initially chosen for Long *et al*'s study using a task that identified electrodes in the two ears that had similar pitches. Listeners then performed a two-interval two-alternative forced-choice task with a pair of pitch-matched electrodes, and in which 100-pps pulse trains were presented first with an ITD of 234 μ s leading in one ear, and then the other. If listeners could not reliably identify the location of the second sound relative to the first then a different electrode was chosen in one ear, and the forced-choice task was repeated. Percent-correct scores for the electrode pairs used here and by Long *et al*, based on a total of 40 trials (60 for listener CI 2), are shown in the final column of Table I.

2. Stimuli—In the diotic² condition, synchronized pulse trains (<1 μ sec resolution) were presented to the two devices using custom software driving the SPEAR3 experimental processor (HearWorks Pty Ltd). Each pulse was biphasic, had a duration of 25 μ sec per phase with an inter-phase gap of 7.4 μ sec (listener CI 2) or 45 μ sec (listeners CI 1, CI 3, CI 4), and was presented in monopolar (“MP1+2”) mode. The dichotic condition was the same as the diotic condition except that the pulse rate presented to the left ear was the same in all three intervals of each trial. For the two standard intervals the stimuli were the same as for the standard intervals in the diotic condition, and were therefore the same in the two ears. In the signal interval the listener was presented with the standard rate in the left ear and the higher rate in the right ear. This introduced a timing difference between the pulses in each ear, potentially allowing the listener to use binaural mechanisms to perform the task. The standard rate was always 100, 200, 300 pps for listeners CI 2,3, and 4; listener CI 1 was additionally tested at a standard rate of 400 pps. The interval between stimuli in each trial was 500 ms.

The level of the pulse train in each ear was selected to be close to its “most comfortable level (MCL)” when presented alone, and to produce a centered image when the two ears were stimulated diotically at a rate of 100 pps. As in the study by van Hoesel (2007), the levels that were presented to each ear did not differ with baseline rate. Also as in van Hoesel's study, listeners reported hearing the diotic stimulus in the center of the head at all rates. The effects of any deviation from a perfectly centered image on performance in the dichotic condition would, as van Hoesel noted, have been reduced by the use of a forced-choice task, and, in addition, by the fact that the signal in the dichotic condition contained ITDs that, at different times throughout the stimulus, passed through the entire range of possible values (see below).

One aspect of the overall design that differed from that used in some previous studies (Carlyon and Deeks, 2002; van Hoesel, 2007) was that the dichotic condition was compared to diotic rather than monotic stimulation. An advantage of the present approach is that it allowed the two conditions to be compared at the same stimulus level per ear *and* at the

²Although the levels used in the two ears sometimes differed from each other, we use the term “diotic” to describe this condition. Similar terminology was used by van Hoesel and Clark (1997)

same overall loudness. In both types of procedure, superior performance in the dichotic condition can unequivocally be attributed to the use of interaural timing cues. However, in our procedure, rate differences were applied only to the right ear in the dichotic condition, so worse sensitivity to rate differences in that condition could be due to poorer sensitivity to rate differences in the right than in the left ear. Therefore, for a subset of conditions where this happened, we re-measured performance in the dichotic and diotic conditions, and at the same time added monotic measurements for each ear separately.

We chose not to rove the level across the intervals in each trial, as has been used in some other studies. Our reasons for not roving level were that (i) loudness changes only gradually with pulse rate between 100-300 pps (McKay and McDermott, 1998), and so is unlikely to have provided a salient cue, (ii) a loudness rove can nevertheless degrade performance (Baumann and Nobbe, 2004), either by introducing a salient variation in one stimulus dimension that may interfere with the detection of more subtle discriminations in the percept of interest (Melara and Marks, 1990), or via small influences of pitch on loudness (Townshend et al., 1987).

3. Procedure—Each trial had a “3I2AFC” structure, in which two of the stimuli had the same “standard” rate, and where either the second or third stimulus (the “signal”) had a higher rate. The listener was instructed to pick the “odd man out”, and correct-answer feedback was provided visually after each response.

The method of constant stimuli was used. We chose this method in preference to an adaptive procedure because it requires neither that sensitivity is well above chance at the largest signal-standard differences studied, nor that the underlying psychometric function is monotonic. For each standard rate a psychometric function was measured, incorporating four or five values of Δr , which we define as the difference between standard and signal rates. Those values, expressed both in “raw” pulses per second and as a percentage of the baseline rate, are shown in part a) of Table II. Fig 1a shows a schematic of the pulses in each ear for a signal in the dichotic condition with a baseline rate of 100 pps and $\Delta r=10$ pps. For clarity, only the first 200 ms of the stimulus is shown. It can be seen that the delay between the n th pulse in one ear and the n th pulse in the other ear increases up to 100 ms ($1/\Delta r$ sec), at which point the n th pulse in one ear is synchronous with the $n+1$ th in the other. The wide gray line in Fig 1b illustrates this fact: for a Δr of x pps, the ITD between the pulses in the two ears rotates through a whole period once every $1/x$ sec, with a sawtooth function. The number of times this occurred over the 800-ms duration of our stimuli is shown in the penultimate column of Table II. It can also be seen from Fig 1a that the asynchrony between each pulse in one ear and the *nearest* pulse in the other occurs after 50 ms ($0.5/\Delta r$), and is equal to half the period of the baseline rate. This asynchrony is shown by the black dashed line in Fig. 1b, and its mean value across the entire stimulus is shown in the final column of Table II.

A potentially important feature of the present design, as shown in Table II, was that the ITD between adjacent pulses always rotated through a whole period an integer number of times, so that the pulse trains always started *and* ended in synchrony in the two ears. This meant that performance in the dichotic condition could not have been influenced by timing difference between the last two pulses in each ear, unlike the case in some previous studies (van Hoesel and Clark, 1997; Carlyon and Deeks, 2002; van Hoesel, 2007).

Testing was performed in blocks of 40 trials. Each block was preceded by 10 practice trials. For a given standard rate, the procedure started with 40 trials at the largest Δr tested for that rate, in either the diotic or dichotic condition. The same Δr was then tested in the other condition, and the procedure was repeated at successively smaller values of Δr until all such

values had been tested. This procedure was then repeated, but with the order of diotic/dichotic conditions at each Δr swapped, so that there were usually a total of 80 trials for each combination of condition and Δr . In some cases – for example where performance was near chance or ceiling – we omitted some values of Δr from the psychometric function. In addition, when the first 40 trials at the largest Δr tested for a given baseline rate yielded a score of 39 or 40 correct responses, and when performance at the next-lowest Δr was above chance, testing was sometimes stopped after 40 trials. The order in which the standard rates were tested differed across listeners. Listener CI 1 completed the 400-pps rate first, followed by 100, 200, and 300 pps. The order for CI 2 and CI 3 was 100, 200, 300 pps, and that for CI 4 was 200, 100, 300 pps.

Results and Discussion

1. Psychometric functions and estimated DLs—Figure 2 shows psychometric functions for each listener and standard rate, with scores in the diotic and dichotic conditions indicated by circles and triangles, respectively. In the diotic condition, these functions are monotonic, and generally reveal a pattern of decreasing performance with increasing rate. To further examine the effect of baseline rate on performance in the diotic condition, we estimated rate DLs by linear interpolation between the points on each function straddling 70.7% correct; this is the value on which “two-up one-down” adaptive procedures converge (Levitt, 1971). The resulting DLs are shown in Table III, with the case where performance does not reach 70.7% indicated by an asterisk (CI 3, 300 pps). The results show that DLs increase with increasing base rate, in line with the results of numerous studies employing monotic stimulation (Shannon, 1983; Tong and Clark, 1985; Townshend et al., 1987; McKay et al., 2000; van Hoesel, 2007).

In the dichotic condition, two listeners, CI 1 and CI 2, show a clear advantage over diotic stimulation at standard rates of 100 and 200 pps, for all values of Δr at which performance is not at chance or ceiling. However, at 300 pps the dichotic advantage disappears, and, for listener CI 2, turns into a *disadvantage*. The dichotic advantage is also absent for CI 1 at a standard rate of 400 pps (filled symbols), and turns into a disadvantage at $\Delta r=10\%$ ($p=0.027$, based on a test of differences between independent proportions³). Results from these two listeners therefore indicate that, once the rate is sufficiently high for diotic rate discrimination to deteriorate, no advantage can be gained by adding a binaural cue. A similar finding was also obtained in the three listeners tested by van Hoesel (2007).

The results from listener CI 4 differ slightly from those of the first two listeners. She shows a small dichotic advantage at a 100-pps pulse rate, but only for the two lowest values of Δr , and the difference is significant only at $\Delta r=5\%$ ($p=0.002$). As with CI 1 and CI 2, performance in the dichotic condition deteriorates relative to that in the diotic condition as rate increases, here becoming worse than in the diotic condition at 200 as well as at 300 pps. Listener CI 3 shows a dichotic advantage for the lowest Δr at 100 pps ($p=0.019$), but performance is worse in the dichotic than in the diotic condition both at higher values of Δr , and at higher standard rates. A striking finding obtained with this listener is that, at a rate of 100 pps, performance in the dichotic condition deteriorates as Δr increases from 2.5 to 10%, a finding which is statistically significant ($p=0.003$). Other instances of these “reversals” occurred for CI 1 at 300 pps, when Δr was increased from 0.83% to 2.5% ($p=0.027$), and for CI 4 at 100 pps when Δr was increased from 5 to 10% ($p=0.035$). A possible explanation

³The test is based on estimates of the standard error of the difference between two proportions, which is equal to $\sqrt{pq[(1/N_1)+(1/N_2)]}$, where N_1 and N_2 are the number of trials on which the two proportions are based, and where p is equal to the proportion correct across all trials making up the two proportions, and $q=1-p$. The normal variate z is then given by the difference between the two proportions divided by the standard error (Ferguson, 1989, p 173-175). It is used here, without Bonferroni correction, for all comparisons between pairs of scores obtained for a single subject.

comes from the fact that, as Δr increases, so does the number of times the “asynchrony” between pulses in the two ears rotates through one cycle during the stimulus (Table II, penultimate column). It may be that listeners have difficulty in exploiting dichotic cues when the amount of asynchrony between pulses in the two ears is changing rapidly, a finding reminiscent of the results previously obtained in NH listeners by Grantham and Wightman (1978). At the same time, as Δr increases, the “pitch” cue available in the right ear becomes more salient, and so the change in performance with increasing Δr will reflect a tradeoff between the ability of the listener to take advantage of this cue, and his/her ability to exploit interaural asynchronies that change quickly over time.

2. Further investigation of worse performance in dichotic than diotic conditions

—In order to investigate that minority of cases where performance was worse in the dichotic than in the diotic condition, a small set of additional measures was obtained from each listener. These measurements were made for a single combination of baseline rate and Δr for each listener, and included estimates of performance for each ear stimulated alone, together with repeats of the measures obtained in the dichotic and diotic conditions. They were obtained between 11 and 20 months after the original psychometric functions were collected.

The results obtained for listener CI 1 at 400 pps and $\Delta r=10\%$ are shown in Table IVa. Performance in the diotic and dichotic conditions had not changed much in the 20 months between tests, although that in the diotic condition had worsened slightly. Combined across the two sets of data, performance was worse in the dichotic than in the diotic condition ($p=0.02$). One possible reason for this is suggested by the new monotic measures, which showed that performance was better in the left than in the right ear. The fact that the rate in the left ear was fixed across intervals in the dichotic condition may have led to the poor dichotic performance. In contrast, the same cannot be said for listener CI 2 at a rate of 300 pps and $\Delta r=35\%$ (Table IVb). Although performance remained worse in the dichotic than in the diotic condition, the better monotic performance occurred with right-ear stimulation. If, in the dichotic condition, the listener could have selectively processed the input from the right ear alone, he would have obtained a score of 95%. However, the score of 82.5% in the dichotic condition was significantly worse than this ($p=0.01$).

The results from the remaining two listeners were less straightforward. When we re-tested listener CI 3 sixteen months later, using the same stimuli as before, we replicated the finding that at 100 pps and $\Delta r=10\%$, performance was worse in the dichotic than in the diotic condition (Table IIIc). However, at this point the listener complained that the stimulus in her right ear was softer than that in her left. When we increased that level by 8 “current units” (approximately 1.4 dB), performance in the dichotic condition improved, and became *better* than that in the diotic condition. We attribute this to a change in the listener's hearing over time, rather than to us initially having set the right-ear level too low, for two reasons. First, an incorrect level setting would not explain why, in the original measures, performance in the dichotic condition was *better* than in the diotic condition for $\Delta r=2.5\%$, but *worse* when $\Delta r=10\%$ (Fig. 2). Second, using the original levels, listener CI 3 was the best of all at discriminating static ITDs of plus and minus 234 μs , and it seems unlikely that this would have been the case if the relative levels at the two ears was such that the percept was dominated by the input from one ear.

When listener CI 4 was re-tested after a delay of 11 months at a rate of 200 pps and Δr of 10%, performance in the diotic condition had inexplicably dropped, so that it was no better than in the dichotic condition.

In summary, the results of our additional measures indicate that, in some cases, monaural rate discrimination was sometimes, but not always, worse in the right than in the left ear. In those cases, this difference could possibly account for the occasional cases of worse performance for the dichotic than for the diotic condition. For those subjects, the difference could also possibly counteract a true dichotic advantage in other conditions. However, this difference occurred only for some subjects, and is unlikely to account for other aspects of the results, such as the nonmonotonic psychometric functions sometimes observed in the dichotic condition.

3. Conclusion—The main conclusion to be drawn from experiment 1 is that there is no evidence that the “upper limit” on rate discrimination can be improved, in CI users, by adding a dichotic cue. Hence the limitation does not seem to be specific to tasks requiring listeners to compare the rates of two sequentially presented stimuli. This conclusion, if correct, is at odds with Carlyon and Deeks' (2002) finding that adding a dichotic cue *did* improve NH listeners' rate discrimination of a 600-pps pulse train. To determine whether the discrepancy reflects a difference between NH and CI users, or is instead due to differences between the stimuli used in the two studies, we performed a second experiment employing NH listeners. The method, stimuli, and procedure used in experiment 2 were directly analogous to those used in the 300-pps condition of experiment 1.

III. EXPERIMENT 2: NH LISTENERS

A. Method

1. Listeners—Five normal-hearing listeners, three of whom were female, took part. Their ages ranged from 19 to 39 years. All had pure tone thresholds in quiet of less than 15 dB HL at frequencies of 0.5, 1.0, 2.0 and 4.0 kHz in both ears. They all had previous experience of taking part in psychoacoustic experiments, and were paid for their participation.

2. Stimuli—Acoustic pulse trains were generated in the frequency domain by summing a large number of harmonics in sine phase at a sampling rate of 40 kHz. All pulse trains were 800 ms long inclusive of 10-ms raised cosine onset and offset ramps, and had an overall level of 72.5 dB SPL. The number of harmonics used to generate each pulse train was always sufficient to “fill” the frequency range from 1500 to 7800 Hz. The pulse trains to be presented to each ear were played out using 16-bit DACs (CED1401*plus* laboratory interface), passed through a reconstruction filter, and then bandpass filtered between 3900 and 5400 Hz using lowpass and highpass filters in series (Kemo VBF25.03, attenuation = 48 dB/octave). They were then attenuated (TDT PA4) and fed to a headphone amplifier where they were mixed with a continuous diotic pink noise. The pink noise was generated using a custom-built noise generator and had a bandwidth of 20 kHz and a spectrum level at 4 kHz of 27.9 dB SPL. Its purpose was to mask auditory distortion products.

3. Procedure—The method of constant stimuli was used. There was a single standard rate of 300 Hz and eight values of Δr , equal to 0.4167, 0.8333, 1.25, 2.5, 5.0, 10.0, 20.0 and 35% of the standard rate. The rates that were used in this experiment are shown in part b) of Table II. Standard stimuli were always presented diotically. Depending on the condition type, signal stimuli were also played diotically, or were presented to the right ear with a copy of the standard stimulus played simultaneously to the left ear (dichotic conditions). As in experiment 1, a “3I2AFC” procedure was used, with the signal always occurring in either the second or third interval. The inter-stimulus interval was 500 ms and correct-answer feedback was provided after every trial.

In each block of 20 trials the signals had the same value of Δr and the presentation condition (dichotic or diotic) was fixed. Each block was followed by a block with the same Δr but in the other presentation condition. A new value of Δr was then chosen and this procedure was continued until one block had been completed for each Δr and condition. This sequence of blocks was then repeated in reverse order. This whole cycle was continued until between 100 and 140 trials had been completed for every Δr and condition, for each listener. The order in which the different values of Δr were tested was chosen quasi-randomly for each listener.

B. Results

The first five panels of Fig. 3 show psychometric functions for each listener in experiment 2, with the mean data shown in the bottom right-hand panel. Data for the dichotic and diotic conditions are indicated by triangles and circles, respectively. For most listeners there is a clear advantage for the dichotic over the diotic condition, which is greatest at the smaller values of Δr , as revealed by a significant interaction between Δr and condition (two-way repeated-measures ANOVA, $F(7,28)=10.2$, $p<0.01$, Huynh-Feldt sphericity correction). At larger values of Δr performance in both conditions is close to ceiling.

One listener, NH 3 shows the opposite pattern of results, with slightly superior performance in the diotic than in the dichotic condition. We can think of no reason why NH 3's data differed from that of the others, except to note that listeners do sometimes differ significantly in their ability to use binaural cues (Buss et al., 2007). Further tests, the results of which are not shown here, failed to show any improvement in the dichotic condition. NH 3 also shows a "reversal", reminiscent of that observed occasionally in the CI data, as Δr is increased from 5 to 10% ($p=0.011$). Hints of such reversals, which do not reach statistical significance, are also apparent in two places along NH 4's psychometric function. The mean data with NH 3's results excluded are shown by the dashed lines in the lower-right panel of Fig. 3.

IV. DISCUSSION

A. Comparison to previous studies of rate discrimination

The rate discrimination performance reported here for CI users and with diotic presentation is roughly similar to that reported for monotic presentation in a number of studies. Based on a summary of nineteen listeners from five studies, Moore and Carlyon (2005) reported average DLs at 100 pps of 7.3%, with a range from 2 to 18 % across listeners. The DLs shown in Table III range from 2.9 to 6.3%, and so fall in the better half of the range of scores reported previously. As Moore and Carlyon pointed out, part of the variation in the DLs across studies may have been due to differences in procedure. Our use of an odd-man-out task with feedback would have allowed listeners to use any perceptual difference between the stimuli to perform the task, and this, combined with the absence of a level rove, may have contributed to the generally good performance reported here.

At a rate of 300 pps, Zeng (2002) reported DLs obtained from a three-interval three-alternative forced-choice procedure, with no level rove, that had a mean of 22% and ranged from 12 to 29% across CI listeners. (These DLs were estimated from the functions he fitted to his data). The DLs for two of our listeners, CI 2 and CI 4, fell below this range, whereas the DL of 21% for CI 1 was close to the mean performance of Zeng's listeners. Performance for CI 3 was below 70.7% correct, even at a Δr of 35%, and so would have been worse than that of any of Zeng's listeners.

The study most similar to that reported here was performed by van Hoesel (2007). Many of the procedural differences, such as the different way of equating stimulus level across

conditions, the longer stimulus duration employed here, and our use of a diotic rather than a monotic comparison to the dichotic condition, appear to have made little impact: In both studies the use of a binaural cue helps performance at baseline rates of 100 and 200 pps, but either has no effect or hinders performance at higher rates. One possibly important factor, however, is our decision to constrain the values of Δr such that the asynchrony between pulses in the two ears always rotated through an integer number of cycles (Table II, penultimate column). This had two advantages. First, it discouraged listeners from performing the task based on the last pulse in each ear, and forced them to perform the task based on “ongoing” asynchronies. Second, it meant that the non-monotonic psychometric functions sometimes observed in the dichotic condition could not be caused by an increase in Δr *reducing* the average asynchrony throughout the waveform. It is also worth noting that the functions in the *diotic* condition were always monotonic, which is evidence that the reversals sometimes seen in the dichotic conditions were not simply due to variability in our data.

B. Limitations on performance in rate discrimination and binaural tasks

The experiments reported here studied performance with and without binaural cues, both with electric and with bandpass filtered acoustic pulse trains. Both types of stimulus differ from acoustic pure tones presented to NH listeners in the way that they are represented at the level of the auditory nerve (“AN”). Specifically, neither stimulus produces “place of excitation” cues, neither produces the steep transitions in the phase response of the AN fiber array that have been observed with pure tones (Kim et al., 1979; Kim et al., 1980; van der Heijden and Joris, 2003), and both present low-rate temporal information to AN fibers normally tuned to higher frequencies. In both cases, as the pulse rate increases, performance deteriorates both on monotic rate discrimination tasks and on tasks requiring binaural processing. This subsection briefly reviews the “high rate” deteriorations observed, and considers whether they share a common origin, as has been suggested by a number of authors (van Hoesel and Tyler, 2003; Griffin et al., 2005). It also compares the deterioration observed with NH and CI listeners, and considers the extent to which the latter group suffers from additional limitations on performance.

1. Rate discrimination without temporal cues—One finding already alluded to is that pulse-rate discrimination thresholds increase with increasing pulse rate (Shannon, 1983; Tong and Clark, 1985; Townshend et al., 1987; McKay et al., 2000; Carlyon and Deeks, 2002). A pertinent finding is that the rate above which performance deteriorates markedly is greater (600 pps) for NH listeners than the 300-pps limit normally observed with CI users (Carlyon and Deeks, 2002). It is however worth noting that there are some exceptions, consisting of “star” listeners who can perform rate discrimination at higher rates (Townshend et al., 1987; Wilson et al., 1997). Work currently ongoing in our laboratory is investigating such instances of exceptional performance with the aim of controlling for potential confounding cues such as level differences and idiosyncratic changes in place-of-excitation with increasing rate. To the extent that such factors can be ruled out, the existence of listeners who can perform rate discrimination up to at least 600 pps indicates that although *most* CI users may suffer rate-discrimination limitations over and above that obtained with their NH counterparts, this limitation may not be a necessary feature of electrical stimulation.

2. ITD discrimination—The discrimination of “static” ITDs also deteriorates with increasing pulse rate, in a way that is not observed when the frequency of a pure tone is increased over a similar range. For CI listeners, van Hoesel and Tyler (2003) reported ITD thresholds that ranged between 90 and 250 μ s across listeners for a 50-pps pulse train, but which increased markedly as pulse rate was raised to 200 pps. At the next-highest rate

tested, which was 800 pps, no listener could perform the task. More recently, van Hoesel (2007) reported ITD thresholds of between 55 and 220 μ s for 100-pps trains, that increased to about 300 μ s at 300 pps; at the highest rate tested of 600 pps, two listeners had thresholds of about 400 μ s and one could not perform the task. Majdak et al (2006) asked listeners to perform lateralization judgements on pulse trains that were amplitude modulated by a common trapezoidal envelope in the two ears, and measured the effects of ITDs between the pulses in the two ears. Sensitivity to these “fine structure” ITDs differed markedly across CI listeners, but two of them showed some sensitivity at pulse rates as high as 800 pps. This was *higher* than the 600-pps “upper limit” observed when acoustic pulse trains, filtered in a way similar to those used here, were presented to NH listeners. However, it should be borne in mind that, at and above 600 pps, the frequency components of the acoustic pulse train would have been resolved by the peripheral auditory system. As Majdak *et al* pointed out, this would have reduced the modulation depth of the 600-pps acoustic stimuli at the output of the peripheral auditory filters, possibly limiting performance in the NH group. It is therefore not clear whether the high-rate deterioration observed with CI listeners would be more or less serious than that observed with NH listeners if the effects of peripheral auditory filtering could be ruled out.

3. Interaural decorrelation—The binaural cue introduced by the dichotic conditions used here at high pulse rates can probably best be described as interaural decorrelation; none of our NH listeners reported hearing binaural beats at 300 pps, and instead described the signal interval as differing in the width or diffuseness of the binaural image. Some of our CI listeners did report hearing some movement in the signal interval for low baseline rate (e.g. 100 pps), but, as noted already, performance on this task deteriorated as baseline rate increased from 100 to 300 pps. This deterioration is reminiscent of that observed for ITDs between equal-rate pulse trains (van Hoesel, 2007). One possible reason for both findings is suggested by Hafter et al's (1983) observation that the improvement in ITD discrimination with increasing duration is smaller at high than at low (acoustic) pulse rates in NH listeners, consistent with ITD judgements being dominated by the first pulse under such conditions (Saber, 1996; Freyman et al., 1997). Indeed, recent physiological measurements suggest that the sensitivity of cells in the inferior colliculus to ITD differences between electric pulse trains may be dominated by the first pulse in each at high, but not at low, rates (Smith and Delgutte, 2007). Hence it is possible that, for ITD discrimination, performance is poor at high rates because listeners cannot effectively combine information across pulse pairs. For our task, dependence on the first pulse pair would have had an even graver consequence, as this pair was always simultaneous in the two ears. However, an additional possible reason for this finding is that the average asynchrony between the pulses in the two ears decreased from 2.5 ms for a 100-pps train to 0.83 ms at 300 pps (Table II, penultimate column).

Some evidence that the limitations on interaural decorrelation detection at high pulse rates differs from that observed for rate discrimination comes from the study by Carlyon and Deeks (2002). They found, in NH listeners, that the effect of frequency region on performance in rate-discrimination tasks with monotic presentation is different from that observed when binaural cues are available. The highest baseline rate at which listeners could perform a monotic rate discrimination task was greater for pulse trains filtered into a “very high (VHIGH)” frequency band (7800-10800 Hz) than into a “HIGH” band (3900-5400 Hz). Conversely, when a contralateral standard was added, performance was better in HIGH than in the VHIGH band. This might indicate that the origin of the high-rate limitation is different in the two tasks, but could also be due to generally poorer overall sensitivity of the binaural system for stimuli presented in very high frequency regions (Bernstein and Trahiotis, 1994), which might occur independently of overall rate.

Further evidence on the detection of interaural decorrelation in high-frequency stimuli comes from the fact that one can measure a binaural masking level difference (BMLD) using transposed narrowband noises as the masker, to which (prior to transposition) in- or out-of-phase low-frequency sinusoids are added (van de Par and Kohlrausch, 1997). We have recently replicated this finding and shown that approximately half of the BMLD disappears when, in the NoS π condition, the stimuli are processed so that envelope modulations slower than 50 Hz are identical in the two ears (Long et al., 2006a). Hence the BMLD for transposed stimuli appears to be strongly dependent on slow (<50 Hz) interaural fluctuations. More striking evidence came from an experiment that used an electrical analog of this technique, in which the low-frequency stimuli modulated 1000-pps pulse trains: CI users exhibited a BMLD whose size was similar to that seen for NH listeners using transposed stimuli, but which disappeared *entirely* when the interaural fluctuations slower than 50 Hz were equated between the two ears (Long et al., 2006b). This finding suggests that the reliance of the BMLD on slow interaural fluctuations is even greater for CI listeners than for NH listeners presented with transposed stimuli. It is also consistent with our suggestion that the decreases in performance occasionally observed with increasing Δr in the dichotic condition of experiment 1 may have been due to the increased rate at which interaural differences changed over time.

4. Conclusions—Overall, our results, combined with those of others, are consistent with the following scenario. In NH listeners, as pulse rate increases, there is a drop in sensitivity to rate differences using either binaural or purely monotic cues. There is *some* evidence that this “upper limitation” has a different origin for binaural processing than for monotic rate discrimination; performance at high rates is better in the VHIGHS than HIGH region for the monotic task, but the opposite is true when a binaural cue is available (Carlyon and Deeks, 2002). In addition, at high rates, sensitivity can be improved by the addition of a binaural cue. However, for most CI listeners, there is an additional source of limitation. This is reflected in the fact that performance in monotic rate discrimination tasks usually breaks down above about 300 pps, compared to around 600 pps in NH listeners. This additional factor also appears to limit performance in binaural tasks. The source of the additional limitation is unclear, but could arise at the level of the auditory nerve, where deficits such as cell loss and absence of spontaneous firing rates are known to occur. Another possible explanation is that AN firing to acoustic pulse trains may have been more stochastic than that to electrical stimuli, a factor which could have been enhanced by the addition of background noise in the NH experiments.

It is interesting to note that the above conclusion differs at least slightly from the one reached by van Hoesel (2007). His conclusion that “monotic rate discrimination may be subject to additional limitations that do not affect ITD perception” was based on a comparison between data obtained in a monotic rate discrimination task with those on the detection of “static” ITDs as a function of pulse rate. He converted the latter data into a format that could be compared to the former by subtracting the threshold ITD at each rate from the interpulse interval at that rate, and expressing this value as a percentage of the interpulse interval. When he did so, the slope relating threshold to rate was shallower than in the monotic rate discrimination task. However, it is not clear that this conversion corresponds in any way to a calculation that the auditory system would perform during the task. In addition, he noted that, although performance in the static ITD task may have been helped by subjects attending to the first pulse in each ear – a strategy not possible with rate discrimination – this cannot have accounted entirely for performance at high rates because some subjects' ITD thresholds dropped with increasing duration. It remains possible, though, that if subjects had been prevented from detecting ITD on the first pulse – for example by making the first pulse in each ear simultaneous (e.g. Laback et al., 2007) – ITD thresholds would have grown more steeply with increasing rate (and perhaps as much as did the

monotic rate discrimination thresholds). Evidence for this possibility comes from the fact that the improvement with increasing duration was smallest at high pulse rates, suggesting an increased dependence on the first pulse as rate increased.

C. Summary and Overall Conclusions

- (i) Four bilaterally implanted users performed rate discrimination with diotic and dichotic stimulation.
- (ii) In the diotic condition, sensitivity deteriorated as the standard rate increased from 100 to 300 pps, consistent with the results of previous studies employing monotic stimulation.
- (iii) At a standard rate of 100 pps, performance for two CI listeners was greatly superior in the dichotic than in the diotic condition, due to the presence of a binaural cue in the former case. The remaining two listeners also showed a dichotic advantage, but only for small rate differences.
- (iv) As the standard pulse rate increased to 300 pps, performance was never better, and sometimes worse, with dichotic than with diotic stimulation. This is consistent with findings recently obtained in three listeners by van Hoesel (2007), who used slightly different stimuli and methods, and extends that finding to a further four listeners. We conclude that the deterioration in rate discrimination at high rates, commonly observed for CI users, is not specific to tasks that require sequential rate discrimination.
- (v) An acoustic analog of this experiment was performed by presenting filtered acoustic pulse trains to NH listeners, with a standard rate of 300 pps. Unlike the case with CI users, performance was significantly better with dichotic than with diotic stimulation. This suggests that NH listeners are able to take advantage of binaural cues using stimuli that are analogous to the electrical stimuli for which this dichotic advantage breaks down.

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Figure 1.

Part a) shows a schematic of the pulses in each ear for a signal in the dichotic condition with a baseline rate of 100 pps and $\Delta r = 10$ pps. For clarity, only the first 200 ms of the stimulus is shown. It can be seen that the asynchrony between the n th pulse in each ear increases up to 100 ms ($1/\Delta r$ sec), at which point the n th pulse in one ear is synchronous with the $(n+1)$ th in the other. The wide gray line in part b) illustrates this fact: for a Δr of x pps, the ITD between the pulses in the two ears rotates through a whole period once every $1/x$ sec, with a sawtooth function. The dotted black line shows the asynchrony between each pulse in one ear and the *nearest* pulse in the other

Figure 2.

Psychometric functions describing percent correct as a function of Δr for the four CI users who took part in experiment 1. Each row shows the data for one listener, and each column shows the data for one baseline pulse rate. Performance in the diotic and dichotic conditions is shown by circles and triangles, respectively. Error bars show ± 1 standard error, estimated from the normal approximation to the binomial distribution. The solid symbols in the top-right panel show performance at a rate of 400 pps for listener CI 1.

Figure 3. Psychometric functions describing percent correct as a function of Δf for the five NH listeners who took part in experiment 2. Mean data are shown in the bottom right panel. Performance in the diotic and dichotic conditions is shown by circles and triangles, respectively. Error bars show +/- one standard error, which, for the individual listeners' data, were estimated from the normal approximation to the binomial distribution. Dashed lines in bold type show the mean data with listener NH 3 excluded.

Table 1

Details of the cochlear implant users who participated in the experiments. The table shows their Patient ID (Pt ID), Date of Birth (DOB) and information for the left ear and then the right ear and finally the Time without Binaural Hearing (in years) and Time with No Hearing (in years). For the left and right, we give Etiology, Date of Deafness Onset (in years), Date of Implant Switch on (in years), Electrode used in experiments, Dynamic range of electrode (dB). The final column shows their performance in a task requiring them to discriminate between a 100-pps pulse train leading by $\pm 234 \mu\text{s}$ to the left vs. the right ear.

Pt ID	DOB	Etiology (Left)	Date of Deafness Onset (Left)	Date of Implant Switch on (Left)	Electrode Used (Left)	Dynamic Range (Left; dB)	Etiology (Right)	Date of Deafness Onset (Right)	Date of Implant Switch on (Right)	Electrode Used (Right)	Dynamic Range (Right; dB)	Time without Binaural Hearing (Years)	Time with No Hearing (Years)	$\pm 234 \mu\text{s}$ 100-pps ITD (%)
CI 1	1969	Progressive bilat.SNHL / PVAS	1991	1998	13	19	German Measles	1991	2001	13	17	10	7	70
CI 2	1934	Noise exposure / idiopathic	1996	2000	13	11	Noise exposure / idiopathic	1989	2002	13	12	13	4	83
CI 3	1926	Progressive	1994	1997	3	11	Progressive	1994	2002	9	9	8	3	90
CI 4	1947	Progressive / Crohns	1990	2002	17	15	Progressive / idiopathic	1991	1999	20	15	11	8	83

Table II

a) The values of Δr used for each standard rate in a) experiment 1 and b) experiment 2. The first three columns show the standard rate, Δr expressed as a percentage of that rate, and Δr in pps. The fourth, penultimate, column shows the number of times the pulses in the two ears rotate in and out of phase during the signal. The final column shows the asynchrony between the pulses in the two ears, averaged over the stimulus duration.

Standard Rate	Δr (%)	Δr (pps)	Rotations	Mean Asynch (ms)
a) Experiment 1				
100	2.50	2.50	2	2.50
100	5.00	5.00	4	2.50
100	10.00	10.00	8	2.50
100	20.00	20.00	16	2.50
200	1.25	2.50	2	1.25
200	2.50	5.00	4	1.25
200	5.00	10.00	8	1.25
200	10.00	20.00	16	1.25
200	20.00	40.00	32	1.25
200	35.00	70.00	56	1.25
300	0.83	2.50	2	0.83
300	2.50	7.50	6	0.83
300	10.00	30.00	24	0.83
300	35.00	105.00	84	0.83
b) Experiment 2				
300	0.42	1.25	1	0.83
300	0.83	2.50	2	0.83
300	1.25	3.75	3	0.83
300	2.50	7.50	6	0.83
300	5.00	15.00	12	0.83
300	10.00	30.00	24	0.83
300	35.00	105.00	84	0.83

Table III

Rate DLs, corresponding to the 70.7% correct, obtained by linear interpolation from the diotic condition of experiment 1. Cases where performance did not reach 70.7% correct are indicated by asterisks.

	100 pps	200 pps	300 pps
CI 1	2.9	9.9	24.3
CI 2	4.3	4.2	8.0
CI 3	6.3	17.4	*
CI 4	3.2	4.6	8.8

Table IV

Summary of additional measures obtained in experiment 1. In parts a, b, and d, the original data (Fig. 2) are plotted, followed by the new data and finally the two sets averaged. In part c (listener CI 3), the original data are followed by some new measures obtained with the same stimulus levels, followed by some additional measures where the level in the right ear was boosted by 8 CUs.

a) 400 pps, $\Delta r=10\%$			
Listener CI 1	July 2005, N=80	March 2007, N=80	Combined N=160
Left		73.75	
Right		58.75	
Dichotic	50.25	55	53.75
Diotic	71.25	61.25	66.25
b) 300 pps $\Delta r=35\%$			
Listener CI 2	April 2006, N=80	March 2007, N=80	Combined N=160
Left		85	
Right		95	
Dichotic	78	82.5	80.63
Diotic	90	98.75	94.38
c) 100 pps, $\Delta r=10\%$			
Listener CI 3	Dec. 2005, N=80	March, 2007 N=40	March 2007 N=80 R ear boost
Left	100 (N=40)	92.5	
Right	40 (N=40)	52.5	60
Dichotic	52.5	45	97.5
Diotic	87.5	72.5	81.25
d) 200 pps, $\Delta r=10\%$			
Listener CI 4	April 2006, N=80	March 2007, N=80	Combined N=160
Left		68.75	
Right		75	
Dichotic	67.5	62.5	65.0
Diotic	91.25	70	80.63