Perceptual differences between low and high rates of stimulation on single electrodes for cochlear implantees

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Previous research has shown that increases in the rate of stimulation on a single electrode yield changes in pitch perception until the rate is increased beyond a given critical rate, after which changes in rate are only perceived as changes in loudness. The critical rate beyond which a rate increase no longer elicits a pitch change in most subjects is approximately 300 Hz, although a small number of subjects have been observed to have critical rates up to approximately 1000 Hz. In this article, we sought to determine if increasing the rate of stimulation beyond the critical rate (up to 12.8 kHz) would eventually result in new changes of perception (other than loudness.) Our data replicate the previously observed results that rates between approximately 300 and 1500 Hz are indistinguishable from each other. However, we observed the finding that a rate of stimulation well above the critical rate (starting between 1500 Hz and 12.8 kHz, depending on electrode and subject) can elicit changes in perception. The perceptual differences between these high rates were sometimes but not always labeled as pitch changes. This phenomenon needs further research to assess its potential relevance to speech perception using high rates of stimulation. © *2005 Acoustical Society of America.* [DOI: 10.1121/1.1830672]

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I. INTRODUCTION

Contemporary cochlear implants and speech-processing strategies are designed to provide electrical stimulation at high pulse rates. By increasing the rate of stimulation, certain elements of a signal can be encoded with finer resolution (such as amplitude or frequency modulation). It has therefore been assumed that higher rates of stimulation are inherently better. However, data examining the relationship between the pulse rate of speech-processing strategies and resulting speech perception performance yield conflicting results across subjects and experiments. The changes in performance from high rates of stimulation could be caused by changes of rate on electrodes individually. Alternatively, higher rates may cause more interaction between electrodes. For example, refractory effects caused by stimulation on one electrode can affect the response to stimulation of nearby electrodes. The experiments presented in this article investigated the perceptual differences between single-electrode stimuli using high rates. The hypothesis was that some subjects experience a change in percept at high rates on individual electrodes. If the hypothesis is confirmed, it might explain part of the variability of speech perception at different stimulation rates.

Loizou *et al.* (2000) studied speech perception performance using a six-channel CIS strategy (Wilson *et al.*, 1991, 1993). They reported that average performance for word and consonant recognition was better at 2100 Hz than at rates below 800 Hz. However, of the six subjects tested, four reached peak performance at either 800 or 1400 Hz. These results suggest that, although higher rates are generally better than low rates, there is a rate of stimulation above which additional rate increments do not affect performance. Wilson *et al.* (2000) found similar results when he examined the effect of rate on a six-channel CIS implementation with four subjects. One subject showed significant improvement in performance with increasing rate only up to approximately 500 Hz/channel, while another showed improvements in performance for rates up to approximately 3500 Hz/channel.

Using the ACE strategy [an n-of-m speech processing strategy (Vandali *et al.*, 2000)] Holden *et al.* (2002) compared speech performance at various sound-pressure levels in subjects using either 720 Hz/channel or 1800 Hz/channel. Subjects' performance was not significantly different for 720 Hz/channel and 1800 Hz/channel with CNC words, CNC phonemes, and CUNY sentences presented at 60 or 70dB. However, for CUNY sentences and CNC phonemes at 50 dB SPL, performance improved from 720 Hz/channel to 1800 Hz/channel. An examination of individual subjects' data reveals that some subjects performed better with the 720-Hz/channel rate, while others performed better with the 1800-Hz/channel rate.

Vandali *et al.* (2000) reported contrary results. Using an n-of-m strategy (a prototype of the ACE strategy), they compared speech comprehension at 65 dBA using speech processor rates of 250, 807, and 1615 Hz/channel. Using a fixed number of maxima of eight (the subset of channels selected in each stimulation cycle), no differences in performance were found between the 250-Hz/channel and 807-Hz/channel conditions. However, significantly poorer performance was found for the 1615-Hz/channel condition. Although the paper indicates that the poorer results for the 1615-Hz/channel condition are mostly caused by one subject, the data do not

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support the hypothesis that higher rates of stimulation yield improved performance.

Other experiments have been performed that examine speech perception performance as a function of rate of stimulation. However, these experiments covaried other parameters with rate of stimulation. For example, some experiments reduced the number of channels as they increased the rate of stimulation per channel in order to maintain a total rate of stimulation below the maximal rates of which the implants are capable. Brill *et al.* (1997) examined speech performance with a CIS strategy, varying the number of channels and rate per channel in order to maintain a fixed overall rate of stimulation. For their three subjects, Brill *et al.* found that the condition for optimal performance for a fixed overall stimulation rate varied across subjects. They concluded that ‘‘trading channels for higher stimulation rate can improve performance, at least for some patients.’’ Because the rate of stimulation was not examined independently from the number of channels, it is difficult to draw conclusions about the effect of rate of stimulation alone.

Kiefer *et al.* (2001) compared speech comprehension performance within subjects for the three most common commercial speech processing strategies, SPEAK (Seligman and McDermott, 1995; Skinner *et al.*, 1994; Whitford *et al.*, 1995), ACE, and CIS. They found that performance was best for all subjects using either ACE or CIS, which are both strategies implementing high rates of stimulation. The SPEAK processing strategy which stimulates at rates between 200 and 300 Hz was not as good as the higher rate strategies. However, most of the subjects for whom CIS was the optimal strategy performed better at 1200 Hz than they did at 1800 Hz. An analysis of the rate of stimulation in this experiment is confounded by the same trade-off Brill *et al.* (1997) encountered as the 1200-Hz map utilized 12 channels and the 1800-Hz condition utilized only six channels. It is therefore difficult to draw a strong conclusion from this experiment as to whether or not rate of stimulation as an independent variable affects performance once the rate of stimulation has exceeded the 250-Hz rate of the SPEAK strategy.

The data examining different rates of stimulation for speech-processing strategies provided conflicting conclusions regarding performance improvements with increasing rates of the processing strategies. Nevertheless, the trend has been to increase the rate of processing strategies, with the expectation that higher rates of stimulation are able to carry more information.

The per-channel rates are increased with the assumption that increased rates lead to increased information without a change in the perceptual quality. This assumption is based on data suggesting that there is a rate saturation point on single electrodes after which additional increments in rate do not change the percept of the stimulus except for changes in loudness. The rate representing the saturation point varies across subjects and experiments. Several papers have suggested that the saturation point is about 300 Hz (Blamey *et al.*, 1984; Shannon, 1983; Tong *et al.*, 1983; Zeng, 2002). Simmons *et al.* (1981) suggest the point is 350 Hz. Eddington *et al.* (1978) found the rate saturation point to lie between 70 and 400 Hz. However, a few experiments have reported discrimination of higher rates. Townshend *et al.* (1987) tested three subjects. One of these subjects had a rate saturation point of approximately 175 Hz, while the other two could distinguish between rates of 1000 Hz and below. Wilson *et al.* (2000) showed data from two subjects, one of whom had a saturation point of 500 Hz while the other had a saturation point of 1000 Hz.

While the exact value of the saturation point varies across subjects and experiments, all of these experiments show that there is a rate beyond which no perceptual differences are detected (other than loudness changes.) The procedure for locating these saturation points involves measuring the just-noticeable difference between a given rate and a higher rate. If the just-noticeable difference becomes very large or immeasurable, then the subject is declared to not be able to distinguish that rate from rates above it. The assumption is often made that all rates above this saturation point are indistinguishable. However, it is possible that there is a range of rates beginning at the saturation point which are perceptually indistinguishable from each other, but rates higher than this range would be perceptually different from the saturation rate. With the tendency to increase the per-channel rate of stimulation to rates well above saturation points, it is important to know whether or not there actually are perceptual differences at higher rates. Perceptual differences at rates well above the saturation point could affect performance and perceptual quality of high rates of stimulation on multichannel speech processors.

In the following studies, we examined the ability of implantees to discriminate different rates of stimulation on single electrodes ranging between 100 Hz and 12.8 kHz. The procedures were repeated for a basal, an apical, and a medial electrode for all subjects. Experiments 1 and 2 investigate discrimination of rates in the ranges of 100 to 1500 Hz and 600 Hz to 12.8 kHz, respectively. The experiments investigated whether higher-rate stimuli could be ranked in order of pitch.

II. EXPERIMENT 1

A. Subjects and methods

Seven users of the Nucleus CI24 implant participated in the study. All normally used an n-of-m strategy (either SPEAK or ACE). Details of the etiology of deafness and implant use are presented in Table I.

All stimuli were presented to subjects by means of a SPEAR speech processor (HearWorks Pty. Ltd., 2003) that was controlled by a personal computer using custom-written software. Stimulation consisted of constant-rate biphasic pulses in monopolar mode (in which current flows from an electrode implanted in the cochlea to two extracochlear return electrodes, MP1+2) on a single electrode for 500 ms. All stimuli were presented with a phase duration of 26 μs and an interphase gap of 8.4 μs. Stimuli varied only in which electrode was used, the rate at which the stimulation occurred on that electrode, and the current level needed to maintain the required loudness. For each subject, three electrodes were chosen to represent an apical, basal, and a medial electrode. Electrode choices for each subject are listed in

TABLE I. Subject details. The ''electrode array'' column refers to which Nucleus CI24 device was used. Straight refers to the CI24M and Contour refers to CI24R (CS).

Subject	Age when profoundly deaf	Years of profound deafness	Etiology	Strategy	Rate per channel (Hz)	Electrode array	Electrodes used
AB	61	14	ME infections as a child.	ACE	1800	Contour	6,13,20
BK	19	50	Unknown	ACE	500	Contour	6,13,20
DC	Unknown	Unknown	Noise exposure	ACE	900	Contour	6,13,20
FZ	58	10	Unknown	ACE	1200	Straight	6,13,19
GB	77	1	Noise exposure	SPEAK	250	Straight	6,13,20
JM	57	4	Meniere's	SPEAK	250	Contour	3,12,20
MM	34	5	Unknown	ACE	900	Straight	5,13,19

Table I. Stimulation rates included the range from 100 to 1000 Hz in 100-Hz steps, as well as 1500 Hz.

1. Loudness balancing

Maximum comfortable current levels (C-levels) were measured for all stimuli using an ascending method of adjustment. Current levels were increased for each stimulus until they were just slightly too loud for comfort and then reduced to the point where they were loud but comfortable again.

For each electrode, all the stimuli were loudness balanced to the C level of the 600-Hz stimulus. Two separate procedures were used for the loudness balancing. The first procedure (used for subjects FZ, AB, GB, and JM) consisted of repeatedly playing one stimulus followed by the other stimulus with a 500-ms interstimulus interval (ISI). The second (test) stimulus to be presented was initially much quieter than the first stimulus so that it was easy for the subjects to differentiate between the two sounds. Subjects were instructed to adjust the loudness of the test stimulus using a toggle switch until the loudness of the two stimuli was the same. They were encouraged to raise the loudness of the second stimulus until it was slightly louder than the first stimulus, and then reduce the loudness until the levels matched. This procedure was then repeated, adjusting the current level of the other stimulus. The differences in current levels between the two balanced stimuli were averaged to calculate the current level of the test stimulus that matched the loudness of the 600-Hz stimulus.

Some subjects (MM, BK, and DC) had difficulty with the previous loudness-balancing procedure. For these subjects, the loudness balancing procedure was an adaptive 2-interval, forced-choice task. In this procedure, the reference and test stimuli were presented once with a 500-ms ISI between them. After hearing the two sounds, subjects pressed a button on a response box corresponding to which of the two stimuli was louder. The loudness of the test stimulus was adjusted up or down for the next trial based on whether the subject considered the test stimulus softer or louder than the reference stimulus. After ten reversals had been made, the last six reversals were averaged to calculate the current level for the test stimulus that matched the loudness of the 600-Hz stimulus. The procedure was repeated using the test stimulus as the standard stimulus and the 600-Hz stimulus as the adjustable stimulus. These data were used to calculate the current level of the loudness-balanced test stimulus in the same way as used in the first loudness-balancing procedure.

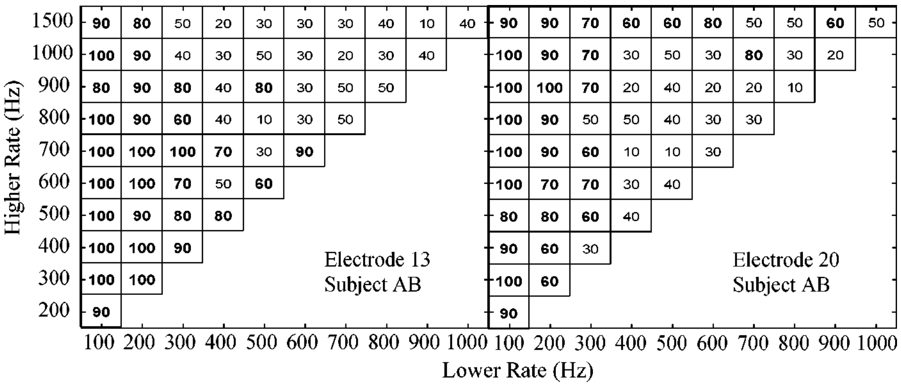
2. Pulse rate discrimination

Pulse rate discrimination was assessed using a 4-interval, forced-choice task. In each trial, four stimuli were presented on the same electrode; three stimuli were presented at one rate of stimulation while the fourth stimulus was presented at another rate of stimulation. Each stimulus was separated with a 500-ms ISI. The amplitude of each stimulus was set randomly per presentation to be within ±2 current levels of the loudness balanced levels to minimize loudness cues. A current level step is about 0.18dB. A ±2 current level jitter should be sufficient to minimize loudness cues, as an analysis of variability of our loudness balancing yielded a 95% confidence interval of ±0.78 current steps.

Subjects were instructed to identify which of the four sounds was different from the others in any way except loudness. Subjects pressed a button on a response box corresponding to the interval with the different sound. The computer recorded button presses. A block of trials consisted of 110 trials on one electrode where all 11 rates of stimulation were compared to the other ten rates of stimulation. Each block was repeated five times for each of three electrodes. Thus, there were ten comparisons for each rate pair (five in each order).

B. Results

To analyze the data, we looked at the percentage of times a subject was able to correctly identify which stimulus was different for each stimulus pair. The ability to detect a difference was declared to be significant if the subject was able to distinguish between two stimuli 60% or more of the time. With a chance level of 0.25, the probability of getting 60% or more correct by chance is less than 0.02. Many comparisons are made in this experiment, which increase the chances of type I errors. With $\alpha = 0.02$, we expect 1 in 50 indistinguishable differences to be found to be significantly different. This is acceptable because this rate of type I errors



Electrode 13, Subject AB

1500	**90**	**80**	50	20	30	30	30	40	10	40
1000	**100**	**90**	40	30	50	30	20	30	40	
900	**80**	**90**	**80**	40	**80**	30	50	50		
800	**100**	**90**	**60**	40	10	30	50			
700	**100**	**100**	**100**	**70**	30	**90**				
600	**100**	**100**	**70**	50	**60**					
500	**100**	**90**	**80**	**80**						
400	**100**	**100**	**90**							
300	**100**	**100**								
200	**90**									
	100	200	300	400	500	600	700	800	900	1000

Electrode 20, Subject AB

1500	**90**	**90**	**70**	**60**	**60**	**80**	50	50	**60**	50
1000	**100**	**90**	**70**	30	50	30	**80**	30	20	
900	**100**	**100**	**70**	20	40	20	20	10		
800	**100**	**90**	50	50	40	30	30			
700	**100**	**90**	**60**	10	10	30				
600	**100**	**70**	**70**	30	40					
500	**80**	**80**	**60**	40						
400	**90**	**60**	30							
300	**100**	**60**								
200	**90**									
	100	200	300	400	500	600	700	800	900	1000

FIG. 1. Data for subject AB in experiment 1. The x axis represents the lower rate of the two compared rates and the y axis represents the higher rate. The percentage of time the subject was able to identify the correct answer is labeled in the corresponding square. Chance performance is 25%. Significant differences ($p < 0.02$) are shown in bold. The figure on the left represents the data for subject AB on his medial electrode (electrode 13). On electrode 13, AB is able to identify rates of 100 and 200 Hz as being different from higher rates. Performance is also good at detecting the difference between 300 Hz and higher rates. These results are typical of what was found on all subjects and all electrodes except for electrode 20 for subject AB. Data for subject AB on electrode 20 are represented on the right, which shows that subject AB was able to detect well above chance the difference between 1500 Hz and most lower rates.

would not alter the pattern of results. It is the pattern of results that is investigated by this experiment, and not the results of any given rate-pair comparison.

With one exception (subject AB, electrode 20), the results for all subjects and electrodes were similar. Figure 1 shows data for subject AB on electrode 13 on the left and electrode 20 on the right. The data show that on electrode 13 for subject AB, 100 and 200 Hz are differentiable from each other, as well as all higher rates with scores of more than 80% correct. Subject AB also performed well on comparisons between 300 Hz and higher rates of stimulation with an average score of 71.25% correct. However, rates of 400 Hz and above did not seem to be systematically different from each other. These results are consistent with previous findings that have suggested that rate of stimulation up to approximately 300 Hz creates a change in pitch and that at rates higher than 300 Hz, there are no perceptual differences other than loudness (Blamey *et al.*, 1984; Shannon, 1983; Simmons *et al.*, 1981; Tong *et al.*, 1983; Zeng, 2002).

For subject AB on electrode 20, rates between 100 and 300 Hz were easily differentiated from each other and higher rates. Rates between 400 and 1000 Hz were not easily differentiated. However, 1500-Hz stimuli were found to be different from lower rates 7 out of 10 times. Subject AB correctly identified the different stimulus 41 out of 70 times ($p < 0.0001$ with chance at 25%) when 1500-Hz stimuli were compared to rates between 400 and 1000 Hz on electrode 20.

No differences were observed between the apical, medial, and basal electrodes and all subjects showed similar patterns. We therefore collapsed the data across all subjects and electrodes to create Fig. 2. The values in each cell of Fig. 2 represent the number of times the rate pair was discriminated with 60% accuracy ($p < 0.02$). There are 21 data points ($7\ \text{subjects} \times 3\ \text{electrodes}$) represented in each cell. With $\alpha = 0.02$, if subjects were unable to detect any differences, we would expect a type I error in fewer than every other cell. A type I error would manifest itself as an increment of 1 in a cell. Figure 2 shows that 100-Hz stimuli were consistently identified as different than higher rates. Two-hundred-Hz stimuli were identified as different consistently as well, but not quite as often as in the 100-Hz case. Four-hundred-Hz stimuli were not consistently identified as different than higher rates.

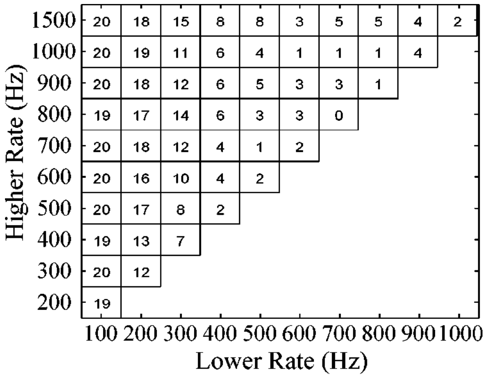
The total number of times a subject correctly identified the different stimulus for each electrode for experiment 1 was correlated with the stimulation rate of the subject's clinical speech processor and no relationship was found ($p = 0.789$).

III. EXPERIMENT 2

A. Subjects and methods

Six of the seven subjects used in experiment 1 participated in experiment 2. Subject MM was unable to participate in this experiment.

Experiment 2 consisted of a higher-rate replication of the previous experiment. The stimuli were steady rate pulse trains presented on a single electrode at 600, 900, 1800, 2400, 3600, 7200 Hz, and 12.8 kHz. Each stimulus was presented for a 500-ms duration. All other stimulus parameters



1500	20	18	15	8	8	3	5	5	4	2
1000	20	19	11	6	4	1	1	1	4	
900	20	18	12	6	5	3	3	1		
800	19	17	14	6	3	3	0			
700	20	18	12	4	1	2				
600	20	16	10	4	2					
500	20	17	8	2						
400	19	13	7							
300	20	12								
200	19									
	100	200	300	400	500	600	700	800	900	1000

FIG. 2. Summary data collapsed across all subjects and electrodes for experiment 1. The values in each cell represent the number of times that the rate pair has been discriminated significantly (60% or better). There are 21 data points ($7\ \text{subjects} \times 3\ \text{electrodes}$) represented in each cell. The figure legends are the same as in Fig. 1. One-hundred- and 200-Hz stimuli are detectably different from each other, and all higher rates in almost all cases. Three-hundred-Hz stimuli show a weaker, but similar pattern. Rates between 400 and 1500 Hz are not reliably detected as different from each other.

remained the same from the previous experiment. Loudness was balanced to C levels at 600 Hz for each subject using the same procedure used for that subject in the previous experiment. The ISI was increased to 1000 ms because of technical limitations in our software. In each block of trials all seven stimuli were paired with the remaining six stimuli. This procedure was repeated five times for each of the three electrodes, yielding ten comparisons per rate pair.

B. Results

Because different patterns are present with different subjects and different electrodes, the data for each subject are presented in Fig. 3. While the results vary, all subjects showed that they could distinguish some high-rate stimuli that are well above their measured saturation points in experiment 1. Data from one of the best performers, subject DC, are on the top row of Fig. 3. Subject DC could generally distinguish rates below 900 Hz from rates above 3600 Hz on all three electrodes. Additionally, subject DC could distinguish many other rates on each electrode. The poorest performer's data are on the bottom row of Fig. 3. This subject (FZ) was unable to differentiate any of the rates between 600 and 7200 Hz on any of his electrodes. He was only able to distinguish 600 and 900 Hz from 12.8 kHz on the medial electrode and 12.8 kHz from 600, 900, 2400, 3600, and 7200 Hz on the basal electrode. On the apical electrode, no sounds were differentiated.

The total number of times a subject correctly identified the different stimulus for each electrode for experiment 2 was correlated with the stimulation rate of the subject's clinical speech processor, and no relationship was found ($p = 0.765$). A significant relationship was found between the total number of times a subject correctly identified the different stimulus on each electrode between experiment 1 and 2 ($p = 0.021$).

IV. EXPERIMENT 3

A. Subjects and methods

The third experiment was a qualitative exploration of the differences between the perceptions of the various high-rate single-electrode stimuli. We explored whether or not the differences in percept could be attributed to pitch, similar to the changes in percept found from a change in rates at low stimulation rates.

Five of the six subjects used in experiment 2 participated in experiment 3. Subject FZ was excluded from this study because he did not show any consistent ability to detect differences between the various high-rate stimuli in experiment 2.

Before performing the experiment, we asked all subjects if they understood the concept of pitch. To help explain the concept of a pitch difference we presented subjects with a 100- and a 600-Hz stimulus on the same electrode, and explained that the 600-Hz stimulus had a higher pitch. We also explained that the difference between a man and woman's speaking voice was usually a difference in pitch, and that a woman's voice is usually higher in pitch than a man's voice. Once we were comfortable that the subject properly understood the difference between high and low pitches (most subjects seemed comfortable with the concept before we addressed the issue), we began the experiment.

The stimuli that were used in this experiment were the same set of stimuli used in experiment 2. Stimuli were presented at the same loudnesses used in experiment 2 with a ±2 current level jitter. In each trial, two different stimuli were presented on the same electrode. The two stimuli were presented with a 1000-ms ISI. Subjects were asked to press one of two buttons on a button box corresponding to the interval containing the higher-pitched stimulus. Each block of trials compared every stimulus with every other stimulus on the same electrode twice for a total of 42 trials in a block. Each trial block was repeated 5 times for each of 3 electrodes totaling 630 trials. Each rate was compared with each other rate a total of 10 times during the 630 trials. An extra trial block was run on subject DC's apical electrode.

B. Results

To analyze the data, we calculated how often each subject rated the higher-rate stimulus as having the higher pitch. If no pitch difference was detected, then expected performance would be at chance level (50%). Scores significantly above chance indicate that higher rates are perceived as having higher pitches, and scores significantly below chance indicate a pitch reversal (that higher rates are perceived as having a lower pitch.) For our first analysis, all pairs of stimuli were analyzed, regardless of whether or not a given pair of stimuli was found to be perceptually different for a given subject in the previous experiment. In examining our data, we found higher rates generating higher pitches, higher rates generating lower pitches, and higher rates producing no pitch changes. Sometimes we found all three patterns in the same subject as was the case for subject DC. Subject DC's data is summarized in Fig. 4.

A strong relationship for higher rates yielding a perception of a higher pitch was observed for subject DC's basal and medial electrodes. Subject DC identified the higher rate stimulation as having the higher pitch 89.05% of the time for the basal electrode and 86.19% of the time for the medial electrode. On the basal electrode, subject DC identified the higher rate of stimulation as having the higher pitch 100% of the time for 12 out of the 21 compared pairs of stimuli. Most of the other rate comparisons on this electrode yielded higher pitch percepts for higher rate stimulation well above the chance level. Subject DC's results for the medial electrode showed similar patterns. For all pairs of stimuli for which there was at least one stimulus with a rate in between the two, subject DC identified the higher rate as having the higher pitch at least 90% of the time.

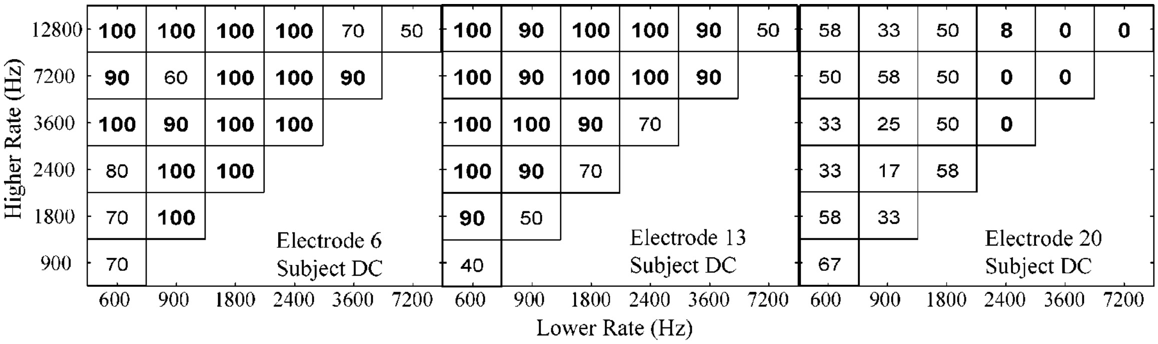
However, this pattern was not found across all subjects and electrodes. The relationship between rate and pitch observed for subject DC's basal and medial electrodes was not present for his apical electrode. When rates between 600 and 1800 Hz were compared with each other or higher rates, either stimulus was approximately equally likely to be rated as having a higher pitch. However, for rates above 2400 Hz, subject DC perceived higher rate stimulation as having a lower pitch on this electrode.

	Higher Rate	Apical						Medial						Basal					
DC	12800	**100**	**90**	**100**	**90**	**80**	50	**90**	**100**	**100**	**100**	**70**	20	**90**	**60**	**80**	50	50	**70**
	7200	**90**	**100**	**100**	**90**	50		**90**	**100**	**90**	**90**	50		**100**	**80**	**70**	50	50	
	3600	**100**	**100**	50	40			**90**	**100**	50	**70**			**70**	**60**	40	40		
	2400	**100**	40	10				30	50	40				**90**	40	30			
	1800	**60**	**70**					30	20					**90**	40				
	900	30						40						**70**					
AB	12800	**90**	**100**	40	50	50	10	**70**	50	30	40	20	40	30	20	40	30	10	50
	7200	**100**	**100**	**60**	10	30		**80**	**90**	40	20	10		50	20	40	40	10	
	3600	**100**	**100**	**60**	50			**80**	**60**	30	20			**70**	**70**	20	20		
	2400	**100**	**90**	30				**80**	**60**	30				**60**	**70**	40			
	1800	**100**	**80**					**60**	50					**70**	**60**				
	900	40						40						**80**					
GB	12800	**90**	**100**	50	30	30	20	**100**	**100**	**80**	40	40	20	**100**	**100**	**80**	**60**	**100**	20
	7200	**100**	**90**	30	50	20		**100**	**100**	50	50	40		**100**	**100**	**70**	**70**	50	
	3600	**100**	**90**	30	40			**90**	**90**	**80**	40			**100**	**100**	**80**	30		
	2400	**90**	**80**	40				**80**	**80**	30				**70**	**80**	30			
	1800	**80**	50					**80**	**70**					**60**	**60**				
	900	10						10						30					
BK	12800	30	50	30	50	30	10	**70**	50	50	**60**	30	30	**70**	**60**	**60**	**70**	**60**	20
	7200	**80**	50	40	50	**70**		**70**	40	**60**	30	30		**60**	**60**	50	40	**60**	
	3600	**90**	40	50	40			40	40	20	**60**			40	30	10	30		
	2400	**90**	**70**	30				50	40	30				30	50	40			
	1800	**90**	**70**					20	30					30	20				
	900	**100**						30						0					
JM	12800	**100**	**100**	**90**	50	40	50	**80**	30	**90**	30	10	10	**100**	**90**	20	30	**70**	**70**
	7200	**90**	**100**	**100**	**70**	30		**90**	**80**	50	50	10		**90**	**80**	50	40	10	
	3600	**90**	**80**	50	20			**90**	50	50	20			**90**	**80**	30	10		
	2400	**90**	**90**	50				**90**	50	30				**100**	50	10			
	1800	**90**	**60**					**90**	**60**					**70**	50				
	900	20						30						**70**					
FZ	12800	30	30	40	30	20	20	**60**	**80**	50	40	40	50	**80**	**60**	50	**70**	**80**	**70**
	7200	30	40	10	20	10		40	20	30	10	20		20	20	30	30	30	
	3600	10	40	30	20			50	0	20	20			20	10	10	40		
	2400	30	40	30				30	20	10				20	40	40			
	1800	20	30					30	50					10	20				
	900	20						10						40					
		600	900	1800	2400	3600	7200	600	900	1800	2400	3600	7200	600	900	1800	2400	3600	7200

Lower Rate

FIG. 3. Data for all six subjects and all three electrodes. The three columns of data represent the basal, medial, and apical electrodes, respectively. The six rows of data represent the six subjects in the experiment. The values in each of the cells indicate the percentage of comparisons where the subject was able to correctly identify the different stimulus. Significant differences ($p < 0.02$) are shown in bold.

While each electrode for each subject showed one of three patterns (higher rate yields higher pitch, higher rate yields lower pitch, rate changes do not affect pitch), there were no consistent patterns across electrodes or subjects. A summary of these data is presented in Fig. 5. Figure 5 consists of a series of box plots for all three electrodes for each subject. Data points were only included in the box plots if, for the same comparison by the same subject, they were



Electrode 6
Subject DC

12800	**100**	**100**	**100**	**100**	70	50
7200	**90**	60	**100**	**100**	**90**	
3600	**100**	**90**	**100**	**100**		
2400	80	**100**	**100**			
1800	70	**100**				
900	70					
	600	900	1800	2400	3600	7200

Electrode 13
Subject DC

12800	**100**	**90**	**100**	**100**	**90**	50
7200	**100**	**90**	**100**	**100**	**90**	
3600	**100**	**100**	**90**	70		
2400	**100**	**90**	70			
1800	**90**	50				
900	40					
	600	900	1800	2400	3600	7200

Electrode 20
Subject DC

12800	58	33	50	**8**	**0**	**0**
7200	50	58	50	**0**	**0**	
3600	33	25	50	**0**		
2400	33	17	58			
1800	58	33				
900	67					
	600	900	1800	2400	3600	7200

FIG. 4. Experiment 3 data for subject DC. The figures from left to right represent results for subject DC's basal, medial, and apical electrodes, respectively. The values in each cell represent the percentage of times the higher rate stimulus was rated as having the higher pitch. There are 10 comparisons per cell for the basal and medial electrodes and 12 comparisons for the apical electrode. Values that are significantly different from chance (50%) for $\alpha = 0.05$ are shown in bold. For subject DC's basal and medial electrodes, the pattern of higher rate stimulation yielding a higher-pitch is very strong. For subject DC's basal electrode, when rates between 2400 Hz and 12.8 kHz are compared, higher rates yield lower pitches. For other comparisons on DC's basal electrode, changes in rate do not seem to yield a change in pitch.

detected as being different at least 60% of the time in experiment 2. Except for one point, subject AB consistently rated the higher rate stimulus as having the higher pitch across all three electrodes. Subject JM found higher rate to yield lower pitch on his basal electrode and no pitch differences on his other electrodes. Subject BK reported higher rate stimulation as having a higher pitch on her basal electrode. On the other two electrodes any pitch differences appear to be a pitch reversal. From these data, the conclusion can be drawn that there are indeed pitch differences for changes in high-rate stimulation for some subjects and some electrodes. However, stimuli that are rated as different in experiment 2 are not always perceived as having a different pitch. Therefore, some of the detectable differences between rates of stimulation must not be in the pitch dimension.

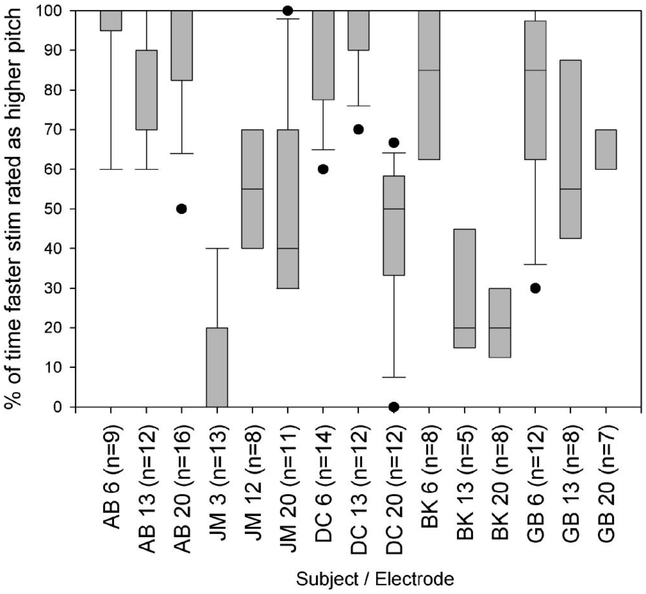


FIG. 5. Boxplot summary data for experiment 3. Each box plot represents the distribution of the data points representing how often the higher-rate stimulus is labeled as having the higher pitch for each electrode and subject. Data points were only included if for the same rate comparison on the same electrode, the subject was able to correctly identify the different stimulus 60% or more of the time. The labels on the *X* axis contain the subject's ID, electrode number, and the number of data points in the corresponding box plot.

V. DISCUSSION

Results for the first experiment are consistent with results found in many other experiments (Blamey *et al.*, 1984; Shannon, 1983; Simmons *et al.*, 1981; Tong *et al.*, 1983; Zeng, 2002). Stimulation on single electrodes for rates up to a saturation point (approximately 300 Hz) were found to produce a perceptual change. All rates above the saturation point were perceptually indistinguishable when loudness was balanced. Unlike the findings of Townshend *et al.* (1987) and Wilson *et al.* (2000), none of the subjects was able to distinguish rates between 400–1000 Hz. With the exception of electrode 20 for subject AB, the 1500-Hz stimulus was not perceptually different from rates between 500 and 1000 Hz. These results suggest that either there are no perceptual differences above approximately 300 Hz or that perceptual changes at high rates generally begin above 1500 Hz.

Experiment 2 provides evidence that there are indeed perceptual changes at high rates above 1500 Hz. Previous experiments had not reported differences at high rates on single electrodes because the highest rates of stimulation examined were not generally over 1000 Hz. However, the results for experiment 2 show that all subjects are able to detect some differences (other than loudness) at rates higher than 1000 Hz. While the high rate required to produce these changes varies across subjects and electrodes, for all subjects except FZ there exists some rate above which changes occur. No relationship was found between rate discrimination performance and the stimulation rate used in the subjects' clinical speech processor.

The data from experiment 3 suggest that some of the detected changes in experiment 2 were pitch changes. However, other detected changes must have been along another perceptual dimension, as they were reliably reported as different but not as higher or lower in pitch. When asked to describe the differences that they heard, some stimuli were described as being different in pitch, while others were reported as changes in clarity or consistency of the sound. No adaptation was reported as there was no evidence of stimuli becoming quieter. However, the 12.8-kHz stimulus was occasionally described as fading in and out. One subject (JM) was able to pick out the 12.8 kHz and occasionally the

7200-Hz stimulus on the apical electrode by recognizing a click at the end of the sound. Electrodograms were made of the 12.8-kHz stimuli to determine if there was anything unusual about the physical stimuli (such as a software artifact). The electrodogram demonstrated that the implant was given the proper instructions for a 12.8-kHz stimuli. We were unable to verify, however, that subject JM's implant was actually delivering the stimulus correctly. To learn more about the click at the end of 12.8-kHz stimuli, we presented them to subject JM for varying durations (from 100 to 2000 ms) and found that regardless of duration, the click always occurred at the offset of stimulation.

On electrode 20, subject DC reported that as rates increased from 2400 Hz to 12.8 kHz the pitch became lower. These results are unlikely to be a result of the subject's confusion of high versus low pitch as the subject reliably rated higher rates as yielding higher pitches for electrodes 6 and 13 and was reliable at labeling pitch changes for low rates (below 300 Hz.) Furthermore, subject DC has had extensive musical training. One possibility is that this percept is created by the refractory periods of auditory neurons. Wilson *et al.* (1997) examined intracochlear evoked potentials for single-electrode pulse trains. He found that for rates of stimulation greater than 400 Hz, the magnitude of the evoked potentials varied with different pulses in the pulse train. Between 400 and 800 Hz, the magnitude of the evoked potentials alternated between two levels. As the rate of stimulation increased, the patterns of the evoked potentials became more complicated with some subjects. Two subjects showed a strong evoked potential every sixth pulse and a weak evoked potential for the seventh pulse at 1016 and 1524 Hz, respectively. Perhaps if the pitch percept we measured is related to the periodicity of the greatest magnitudes of the evoked potentials, then it is possible that higher-rate stimuli produce a lower periodicity. While these results were observed on only one electrode with only one subject, Wilson *et al.* reported differences in responses of neural populations in response to stimulation on different electrodes within a given subject. It is therefore possible that the neural activity in response to the subject DC's apical electrode was different from that for other electrodes and other subjects.

Most current commercial and research speech processing strategies use high per electrode rates of stimulation (Loizou *et al.*, 2003). Higher rates of stimulation allow for greater temporal resolution in stimulation. It is generally assumed that these high rates of stimulation do not cause changes in percepts on single electrodes. However, the data in this article suggest that this assumption is faulty. The perceived changes for different high rates are likely to have an effect on speech perception at different overall rates. If at high rates different rates of stimulation sound different, it is reasonable to assume that speech perception may be affected by the changes in rates. For example, if higher rates of stimulation yield a higher pitch percept, then higher rate-processing strategies may shift the perceived pitches of sounds. While this may or may not cause problems for high-rate strategies, it is important to be aware of these issues when designing or implementing a high-rate strategy.

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Blamey, P. J., Dowell, R. C., Tong, Y. C., and Clark, G. M. (**1984**). ''An acoustic model of a multiple-channel cochlear implant,'' J. Acoust. Soc. Am. **76**, 97–103.

Brill, S. M., Gstottner, W., Helms, J., von Ilberg, C., Baumgartner, W., Muller, J., and Kiefer, J. (**1997**). ''Optimization of channel number and stimulation rate for the fast continuous interleaved sampling strategy in the COMBI 40+,'' Am. J. Otol. **18**, S104–106.

Eddington, D. K., Dobelle, W. H., Brackmann, D. E., Mladejovsky, M. G., and Parkin, J. L. (**1978**). ''Auditory prostheses research with multiple channel intracochlear stimulation in man,'' Ann. Otol. Rhinol. Laryngol. **87**, 5–39.

HearWorks Pty. Ltd. (**2003**). ''SPEAR3 Research System,'' http://www.hearworks.com.au/spear.

Holden, L. K., Skinner, M. W., Holden, T. A., and Demorest, M. E. (**2002**). ''Effects of stimulation rate with the Nucleus 24 ACE speech coding strategy,'' Ear Hear. **23**, 463–476.

Kiefer, J., Hohl, S., Sturzebecher, E., Pfennigdorff, T., and Gstoettner, W. (**2001**). ''Comparison of speech recognition with different speech coding strategies (SPEAK, CIS, and ACE) and their relationship to telemetric measures of compound action potentials in the nucleus CI 24M cochlear implant system,'' Audiology **40**, 32–42.

Loizou, P. C., Poroy, O., and Dorman, M. (**2000**). ''The effect of parametric variations of cochlear implant processors on speech understanding,'' J. Acoust. Soc. Am. **108**, 790–802.

Loizou, P. C., Stickney, G., Mishra, L., and Assmann, P. (**2003**). ''Comparison of speech processing strategies used in the Clarion implant processor,'' Ear Hear. **24**, 12–19.

Seligman, P., and McDermott, H. (**1995**). ''Architecture of the Spectra 22 speech processor,'' Ann. Otol. Rhinol. Laryngol. Suppl. **104 (Suppl. 166)**, 139–141.

Shannon, R. V. (**1983**). ''Multichannel electrical stimulation of the auditory nerve in man. I. Basic psychophysics,'' Hear. Res. **11**, 157–189.

Simmons, F. B., White, R. L., Walker, M. G., and Mathews, R. G. (**1981**). ''Pitch correlates of direct auditory nerve electrical stimulation,'' Ann. Otol. Rhinol. Laryngol. Suppl. **90**, 15–18.

Skinner, M. W., Clark, G. M., Whitford, L. A., Seligman, P. M., Staller, S. J., Shipp, D. B., Shallop, J. K., Everingham, C., Menapace, C. M., Arndt, P. L., Antogenelli, T., Brimacombe, J. A., Pijl, S., Daniels, P., George, C. R., McDermott, H. J., and Beiter, A. L. (**1994**). ''Evaluation of a new spectral peak coding strategy for the Nucleus 22 Channel Cochlear Implant System,'' Am. J. Otol. **15 Suppl 2**, 15–27.

Tong, Y. C., Blamey, P. J., Dowell, R. C., and Clark, G. M. (**1983**). ''Psychophysical studies evaluating the feasibility of a speech processing strategy for a multiple-channel cochlear implant,'' J. Acoust. Soc. Am. **74**, 73–80.

Townshend, B., Cotter, N., Van Compernolle, D., and White, R. L. (**1987**). ''Pitch perception by cochlear implant subjects,'' J. Acoust. Soc. Am. **82**, 106–115.

Vandali, A. E., Whitford, L. A., Plant, K. L., and Clark, G. M. (**2000**). ''Speech perception as a function of electrical stimulation rate: Using the nucleus 24 cochlear implant system,'' Ear Hear. **21**, 608–624.

Whitford, L. A., Seligman, P. M., Everingham, C. E., Antognelli, T., Skok, M. C., Hollow, R. D., Plant, K. L., Gerin, E. S., Staller, S. J., McDermott, H. J. *et al.* (**1995**). ''Evaluation of the Nucleus Spectra 22 processor and new speech processing strategy (SPEAK) in postlinguistically deafened adults,'' Acta Oto-Laryngol. **115**, 629–637.

Wilson, B., Wolford, R., and Lawson, D. (**2000**). ''Speech processors for auditory prostheses'' (Center for Auditory Prosthesis Research: Research Triangle Park, NC), 1–61.

Wilson, B. S., Lawson, D. T., Zerbi, M., and Finley, C. C. (**1993**). ''Recent developments with the CIS strategies,'' in *Advances in Cochlear Implants:*

Proceedings of 3rd International Cochlear Implant Conference, Innsbruck, Austria, April 1993, edited by I. J. Hochmair-Desoyer and E. S. Hochmair (Manz, Vienna), 103–112.

Wilson, B. S., Finley, C. C., Lawson, D. T., and Zerbi, M. (**1997**). ''Temporal representations with cochlear implants,'' Am. J. Otol. **18**, S30–34.

Wilson, B. S., Finley, C. C., Lawson, D. T., Wolford, R. D., Eddington, D. K., and Rabinowitz, W. M. (**1991**). ''Better speech recognition with cochlear implants,'' Nature (London) **352**, 236–238.

Zeng, F. G. (**2002**). ''Temporal pitch in electric hearing,'' Hear. Res. **174**, 101–106.