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Published in final edited form as:
Hear Res. 2021 September 15; 409: 108319. doi:10.1016/j.heares.2021.108319.

Pitch perception is more robust to interference and better resolved when provided by pulse rate than by modulation frequency of cochlear implant stimulation

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Abstract

Cochlear implants are medical devices that have been used to restore hearing to more than half a million people worldwide. Most recipients achieve high levels of speech comprehension through these devices, but speech comprehension in background noise and music appreciation in general are markedly poor compared to normal hearing. A key aspect of hearing that is notably diminished in cochlear implant outcomes is the sense of pitch provided by these devices. Pitch perception is an important factor affecting speech comprehension in background noise and is critical for music perception. The present article summarizes two experiments that examine the robustness and resolution of pitch perception as provided by cochlear implant stimulation timing. The driving hypothesis is that pitch conveyed by stimulation timing cues is more robust and better resolved when provided by variable pulse rates than by modulation frequency of constant-rate stimulation. Experiment 1 examines the robustness for hearing a large, one-octave, pitch difference in the presence of interfering electrical stimulation. With robustness to interference characterized for an otherwise easily discernible pitch difference, Experiment 2 examines the resolution of discrimination thresholds in the presence of interference as conveyed by modulation frequency or by pulse rate. These experiments test for an advantage of stimulation with precise temporal cues. The results indicate that pitch provided by pulse rate is both more robust to interference and is better resolved compared to when provided by modulation frequency. These results should inform the development of new sound processing strategies for cochlear implants designed to encode fundamental frequency of sounds into precise temporal stimulation.

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Keywords

auditory neuroscience; cochlear implants; modulation; pitch; interference

I. INTRODUCTION

Cochlear implants have been used to restore hearing to half-a-million people worldwide. Most recipients learn to hear with this new form of stimulation and achieve high levels of speech comprehension in quiet[1,2], but speech comprehension in noise and music appreciation tend to be poor[3,4]. In particular, pitch perception is poorly conveyed by cochlear implants[5–7]. Given the established connections between pitch perception with speech recognition in noise and with music appreciation, much attention has been given to improving pitch perception for cochlear implant users[8–20]. The present article considers how temporal precision of stimulation affects the salience of pitch provided by electrical stimulation.

Pitch has been aptly defined as the perceptual correlate of acoustic periodicity[21]. In healthy auditory physiology, periodic sounds produce a complex pattern of activity in the auditory nerve[22–28]. One approach for designing stimulation for cochlear implants is to try to recreate the neural response that would be produced in healthy physiology. The challenges for doing so are well documented[29–36]. The fundamental frequency and lower order harmonics of a periodic sound produce spatially resolved peaks in the auditory nerve excitation pattern in healthy hearing[37]. Recreating resolved peaks for multiple harmonics with cochlear implant stimulation is difficult because of limitations associated with the number of electrodes, current spread, neural distance, and neural health. In this manner, the electrode-neural interface limits stimulation place-of-excitation cues for pitch perception.

In contrast, the electrode-neural interface is remarkably capable of conveying pitch cues associated with temporal response properties of the auditory nerve[38]. All cochlear implants in use today can control stimulation timing with sub-microsecond precision[1]. The synchrony of auditory nerve firing is higher for electric compared to acoustic stimulation[39]. Despite this remarkable ability to convey temporal cues to the auditory nerve, most cochlear implants do not use stimulation pulse rate as a way of providing information. In fact, decisions were made decades ago to discard the acoustic temporal fine structure and to only convey relatively slowly varying temporal envelopes[2]. This decision was made in part to mitigate challenges of analog stimulation in which the fast-changing temporal dynamics of stimulation interfered across nearby electrodes. The decision to discard temporal fine structure led to widely successful envelope-coding strategies such as SPEAK, ACE, and CIS, which have provided hundreds of thousands of recipients with high levels of speech comprehension in quiet, but the question remains whether discarding temporal information contributes to poor speech comprehension in noise and to markedly poor pitch perception.

Attempts have been made to improve how temporal cues are provided by cochlear implant stimulation. Some attempts have explicitly tried to encode acoustic temporal fine structure using variable-rate stimulation. The peak-derived timing (PDT) coding strategy triggers pulse timings based on the temporal fine structure of each frequency band of the sound processor[40]. The fine structure processing (FSP) coding strategy triggers pulse timings in a similar way but only for the most apical electrode(s)[41–45]. The PDT strategy has not been implemented for clinical use and most research evaluations of the strategy were conducted as acute laboratory-based evaluations without substantial familiarization. One evaluation of the PDT strategy did provide two to three weeks of familiarization but did not find a significant difference for localization accuracy compared to CIS in bilateral cochlear implant users[46]. In contrast, since the FSP strategy has been approved for clinical use, evaluations have examined long-term outcomes[42]. Studies that have compared FSP to high-definition CIS found that FSP improves speech perception in noise and musical sound quality[42–44].

That variable-rate stimulation (as used in FSP) might provide better pitch perception and/or better spatial hearing compared to amplitude modulation of constant-rate stimulation (as used in CIS-style envelope strategies) is supported by psychophysical comparison studies of normal-hearing listeners. A series of studies demonstrated that spatial localization, particularly interaural timing difference discrimination, is better provided by modulated sounds when the modulation depth is deeper[47–56]. Similarly, there is evidence that pitch is better provided when complex tones have deeper modulation. Specifically, studies have shown that pitch sensitivity is better conveyed by high pass filtered click trains compared to relatively shallow sinusoidally amplitude modulated tones[57,58].

Given the evidence from studies of normal-hearing listeners, several studies have examined aspects of temporal dynamics on cochlear implant electrode psychophysics. A study directly comparing pitch resolution provided by pulse rate to that provided by modulation frequency found a large benefit for pulse rate, particularly for rates above 200 Hz[13]. A later study also found that pitch resolution was better provided by pulse rate than by modulation frequency, but that the depth of modulation was an important factor and that deep modulations synchronized across electrodes provided similar results compared to pulse rate[59]. Several studies, however, provided conflicting results in that no difference in pitch resolution was found when comparing pulse rate and modulation frequency, or when comparing modulation frequencies with deeper modulations[60–62].

In summary, there is evidence that the temporal precision of stimulation can affect pitch perception and localization abilities in cochlear implant users. The evidence is encouraging and suggests that variable-rate stimulation and/or deeper modulations could broadly improve outcomes for cochlear implant users. The evidence, however, is mixed and the present study was designed to test two key hypotheses associated with this overarching thesis. Two experiments are summarized that test whether pulse rate provides benefits compared to modulation frequency when discriminating pitch in the presence of nearby electrical interference. The first experiment tests whether pitch ranking provided by pulse rate is more robust to nearby electrical interference. Listeners were tested to determine how much electrical interference was needed to disrupt their ability to hear an otherwise easily discernible one-octave difference in pulse rate or in modulation frequency. Our hypothesis is that the listeners will be able to make pitch judgements at less favorable target-to-masker levels based on pulse rate compared to modulation frequency. The second experiment tests a related hypothesis, that pitch resolution is better provided by pulse rate than by modulation frequency. In the second experiment, the level of the interfering electrical activity was held constant, and adaptive procedures were used to measure just-noticeable differences for pitch. Together, the two experiments characterize the robustness and resolution of pitch provided by these two methods of stimulation and characterize the fundamental cues available for pitch perception in cochlear implants.

II. METHODS

A. Overview

Adult cochlear implant users participated in two experiments designed to test the robustness (Experiment 1) and resolution (Experiment 2) for making pitch judgements in the presence of interfering stimulation. For both experiments, the main hypothesis is that pitch is better provided by pulse rate than by modulation frequency. In the first experiment, the relative level difference between target and masker was adaptively controlled to characterize robustness of pitch judgements in the presence of masking stimulation. With robustness to interference thus characterized, pitch resolution in the presence of interfering stimulation was measured in the second experiment. Analysis of results focus on the main hypotheses that pulse rate provides a sense of pitch that is both more robust (Experiment 1) and better resolved (Experiment 2) compared to as conveyed by modulation frequency of constant-rate stimulation.

B. Subjects

Seven adult cochlear implant users participated in this study. Four of the subjects were bilateral and were tested in each ear separately, with the first ear randomly selected. All subjects were implanted with devices from Cochlear Corporation and were tested using the USC Cochlear Implant Research Interface[63]. Subjects provided informed consent and were paid for their participation. The experimental protocol was approved by University of Southern California Institutional Review Board. Subject information is provided in Table 1. During stimulation, participants sat in a sound-proof booth and there were no acoustic sounds generated during the test (stimuli were directly delivered to electrodes and bypassed the clinical sound processor). As such, there were no acoustic sounds in the environments aside from ambient sounds which measured less than 40 dB SPL (A-weighted long-term average). Participants who had a contralateral cochlear implant or hearing aid were instructed to turn that device off during testing. None of the participants had substantial residual acoustic hearing defined as having audiometric thresholds less than 60 dB HL at any frequency from 125 to 8 kHz.

C. Loudness balancing as a function of pulse rate

Both experiments examined psychophysical responses using a wide range of pulse rates. Consequently, it is important to balance loudness across pulse rates. Thresholds of audibility and comfortable stimulation levels were measured using a method of adjustment for unmodulated pulse rates from 50 to 6400 pulses per second (pps) and were fit with a logistic equation of the form:

$$Y(x) = U - \frac{U - L}{\left(1 + Qe^{-Bx}\right)^{\frac{1}{v}}},$$

where U and L are the upper and lower limits of the subject's dynamic range, Q is related to charge at 100 pps, B is the rate by which the charge decreases with stimulation rate, x is stimulation rate expressed as $\log_2$(rate/100), and v controls asymptotic growth. All stimulation levels were based on the fitted functions and constrained to be between 90 and 100% of the fitted dynamic range with 10% roving of stimulation levels randomly applied across trials using a uniform distribution.

D. Stimuli

Similar stimuli were used in both experiments and are illustrated in Figure 1. Stimuli were designed in MATLAB and delivered to test electrodes using the USC Cochlear Implant Research Interface[63]. Each trial consisted of two 400 ms intervals separated by 200 ms of silence. Half of the conditions tested pitch ranking conveyed by modulation frequency of constant-rate stimulation (upper panel of Figure 1) and half of the conditions tested pitch ranking conveyed by pulse rate (lower panel). The cue for pitch ranking was either a change in modulation frequency or a change in pulse rate for the target electrode.

The nominal modulation frequency (or pulse rate) was near 220 Hz but with adaptive control and frequency roving as specified in procedural subsections. Most conditions tested pitch ranking in the presence of masking stimulation for which the modulation frequency or pulse rate of the masker was independent of the target. Masking conditions included having the masker co-located with the target, having the masker 2 or 4 electrodes away, and having no masker. The target was presented on electrode 5 (numbering apex to base), so the masking electrode locations were 5, 3, 1, and no masker. All test electrodes were functional with no apparent anomalies in any subject. The nominal modulation frequency (or pulse rate) of the masker was 110 Hz but with 1/4th octave roving independent from the target roving to avoid consistent beat-frequency cues.

Different cochlear implant manufacturers use different schemes for allocating acoustic frequency to stimulating electrodes, it is therefore difficult to generalize how acoustic frequencies are mapped to specific electrodes. But as a reference, the default frequency allocation for Cochlear Corporation devices uses band-pass filters with center frequencies starting at 125 Hz and spaced 125 Hz apart for the ten-most apical electrodes. Referenced to such frequency allocation, the masking electrodes considered in this experiment, spaced 2 or 4 electrodes from the target, would correspond to frequency differences of 250 and 500 Hz. Though we note that frequency allocation can be defined differently across devices.

The test conditions were chosen to consider the case of lower frequency interference near 110 Hz on a higher frequency target near 220 Hz because of evidence that modulation interference is stronger when the interfering modulation frequency is lower than that of the target[60]. The interfering electrode locations (1, 3, 5) were chosen to be apical to or coinciding with the target electrode (5) to reflect that the interfering frequency was lower than the target.

All stimuli were comprised of cathodic-leading, symmetrical, biphasic current pulses with 25 μs phase durations and 8 μs interphase gaps. Stimuli were 400 ms in duration with 100 ms raised-cosine attack and release times applied between detection thresholds and comfortable stimulation levels. Stimuli were presented in monopolar configuration except for subject 10, one of the authors, who tested in bipolar+3 configuration since monopolar configuration is not available for N22 implants. For modulation frequency conditions, the stimulation rate was 6400 pps except for subject 10, who was tested using 2000 pps. Pulse rates of 6400 pps were used for conveying modulated stimuli because pilot testing indicated that some participants could hear beat-frequency distortion when lower pulse rates were used. While previous studies have often used 2000 pps as a pulse rate for characterizing modulated pulse trains, we found that many participants could perceive distortion for that pulse rate. Consequently, we used the higher 6400 pps pulse rate for all participants whose device supported such. Subject 10 was tested using the lower 2000 pps because of device (N22 implant) limitations.

E. Experiment 1 Procedure: Tolerance of Pitch Ranking to Interference

Experiment 1 tested the relative target-to-masker level difference required for subjects to correctly pitch rank stimuli that contained a one-octave difference in modulation frequency or pulse rate. An easily discernible one-octave difference was used to determine the amount of nearby electrical interference was necessary to disrupt the pitch percept. We chose a one-octave difference as a condition that all participants could readily hear as a pitch difference in the absence of interfering stimulation.

The procedure was a two-interval, two-alternative, forced-choice comparison where the participant was asked “Which interval was higher in pitch?”. At the beginning of the procedure, the target was presented at the comfortable stimulation level for the condition as described in Section C. For conditions with a masker, the masker was presented at the measured detection threshold for the masking electrode. After correct answers, the masker level was increased by 5% of the dynamic range between threshold and comfortable stimulation levels until reaching comfort levels. After correct answers when the masker had already been increased to comfort levels, the target was decreased by 5% of the dynamic range. After wrong answers, the masker was decreased by 15% (or the target increased by 15%) of the dynamic range. A run continued until the participant made eight mistakes and the average of the last four reversals was taken as the discrimination threshold for the run. This procedure converges to 75% identification accuracy[64].

Eight conditions were tested including all combinations of two stimulation types (modulation frequency and pulse rate) and four masker conditions (co-located on same electrode, separated by 2 or 4 electrodes, and no masker). Each condition was repeated three times and the order of conditions was randomly assigned for each repetition. The trial-by-trial modulation frequency (or pulse rate) was roved 1/4th octave about the nominal condition frequency of 220 Hz and was randomly roved in level by 10% of the dynamic range while keeping the target-to-masker level differences specified by the adaptive procedure. Frequency and level roving were based on uniform distributions.

F. Experiment 2 Procedure: Resolution of Pitch Ranking with Interference

Experiment 2 tested the resolution of modulation frequency and pulse rate discrimination in the presence of interfering electrical stimulation. In Experiment 2, the level of the interfering stimulation was held constant and adaptive procedures were used to determine the just-noticeable differences for pitch. Pitch resolution was measured using a two-interval, two-alternative, forced-choice procedure in which participants were asked: "Which interval was higher in pitch?".

At the beginning of the procedure, the target-to-masker level difference was set based on the results of Experiment 1; specifically, the highest measured threshold for each subject from Experiment 1 was rounded up to the nearest 10% of the subject's dynamic range with a few exceptions: the target-to-masker difference was never increased above 60% and, in some cases, (e.g., 9L, 9R, 10) a value just below the highest measured threshold was used. The latter decision was made to adjust for the wide difference in performance observed between modulation frequency and pulse rate conditions.

The modulation frequency or pulse rate was adaptively controlled to measure discrimination thresholds. The initial difference was 100% (i.e., an octave) and was decreased by a factor of $\sqrt[3]{2}$ following correct answers and increased by a factor of 2 following wrong answers. This difference was applied to lower the frequency of the reference interval and to raise the frequency of the target interval. Specifically, for each trial, a roved frequency value was selected from a quarter-octave-wide uniform distribution geometrically centered on the condition frequency. Relative to this roved frequency value, the standard frequency was lowered, and the target raised by $\sqrt{(1 + \Delta/100)}$. A run continued until the subject made 8 mistakes and the average of the last 4 reversals was taken as the discrimination threshold. This procedure converges to 75% discrimination accuracy[64]. The same 8 conditions were tested as for Experiment 1. Each condition was repeated three times and the order of conditions was randomly assigned for each repetition.

G. Analyses

Both experiments were full factorial with repeated measures. The main hypothesis of experiment 1 is that pitch ranking is more tolerant to nearby interference when conveyed by pulse rate than by modulation frequency. Similarly, the main hypothesis of experiment 2 is that pitch resolution is better conveyed by pulse rate than by modulation frequency. Initial analyses were run that indicated that repetition of runs was not a significant factor ($p >$ 0.1). For both experiments, two-way repeated-measures analysis of variance was conducted with stimulation method and masking condition as factors. The main hypothesis was tested on the significance of stimulation method as a factor. Planned multiple comparisons were conducted on the effect of stimulation method for each masking condition.

III. RESULTS

A. Experiment 1: Tolerance of Pitch Ranking to Interference

Figure 2 plots the threshold target-to-masker level differences for each subject and condition. In general, subjects had lower thresholds for pulse rate compared to modulation frequency. Most subjects had thresholds less than 0 when listening to pulse rate indicating that they could still perform the pitch ranking task even when the masker was louder than the target. In contrast, when listening to modulation frequency, most subjects had thresholds greater than 0 indicating that they needed a favorable target-to-masker level differences to perform the task. There are notable exceptions, particularly 4R, who had exceptionally low thresholds for both modulation frequency and pulse rate.

Figure 3 plots group statistics for each condition. Average thresholds were better with pulse rate than with modulation frequency ($F_{1,10} = 12.5$, $p = 0.0005$). The effect of masker condition was significant ($F_{3,10} = 33.2$, $p < 0.001$), but the interaction between stimulation method and masker condition was not ($F_{3,30} = 0.70$, $p = 0.56$).

Planned comparisons were made to consider the effect of stimulation method for each masker condition. Effect size was quantified using Cohen's method and significance testing using multiple comparisons with Bonferroni critical values. When comparing pulse rate to modulation frequency, average target-to-masker level differences improved from 32.8 to −0.6 %DR for the co-located masker ($d_{Cohen} = 1.34,\ p = 0.006$), from 28.1 to −4.6 %DR for the masker two electrodes away ($d_{Cohen} = 1.08,\ p = 0.028$), from 21.5 to −7.7 %DR for the masker four electrodes away ($d_{Cohen} = 0.83,\ p = 0.047$), and from −38.5 to −82.9 %DR for the no masker condition ($d_{Cohen} = 1.00,\ p = 0.005$).

Notably, average thresholds measured with interference were greater than 0 for modulation frequency indicating that subjects typically needed a favorable target-to-masker level difference, but average thresholds were less than 0 for pulse rate indicating that the average subject could hear an octave pitch difference even when the masker was louder than the target. In summary, thresholds were lower for pulse rate compared to modulation frequency indicating better tolerance to nearby electrical interference.

B. Experiment 2: Resolution of Pitch Ranking with Interference

Figure 4 shows discrimination thresholds for each subject and condition. Discrimination varies widely across subjects with some having discrimination thresholds between 2 to 5% with interference, while others having thresholds near 10% even without interference. The comparison between modulation frequency and pulse rate typically favored better performance with pulse rate but with much inter-subject variability.

Figure 5 shows group averages and standard errors of the mean for measured discrimination thresholds. Average discrimination thresholds were significantly lower as provided by pulse rate compared to by modulation frequency $\left(F_{1,\,10} = 12.7,\ p = 0.005\right)$. The effect of masker condition was highly significant $\left(F_{3,\,10} = 26.7,\ p = 0.001\right)$ and the interaction between stimulation type and masker condition was moderately significant $\left(F_{3,\,30} = 2.8,\ p = 0.058\right)$.

Planned comparisons were made to consider the effect of stimulation method for each condition. Effect size was quantified using Cohen's method and significance testing using multiple comparisons with Bonferroni critical values. When comparing pulse rate to modulation frequency, average discrimination thresholds improved from 50.5 to 17.6% for the co-located masker ($d_{Cohen} = 1.40,\ p = 0.010$), from 40.5 to 15.1% for the masker two electrodes away ($d_{Cohen} = 1.15,\ p = 0.017$), from 28.3 to 17.2% for the masker four electrodes away ($d_{Cohen} = 0.64,\ p = 0.105$), and from 10.8 to 8.0% for the no masker condition ($d_{Cohen} = 0.45,\ p = 0.048$).

In summary, pitch ranking was generally more tolerant to masking and was better resolved when provided by pulse rate compared to modulation frequency. The advantage of pulse rate compared to modulation frequency was largest when the target and masker were co-located on the same electrode.

IV. DISCUSSION

The results of the experiments reported here indicate that key aspects of pitch perception are better provided by pulse rate than by modulation frequency of constant-rate stimulation. These experiments used controlled electrical stimulation that bypassed clinical sound processing to test the robustness and resolution of pitch in the presence of interfering stimulation. In so doing, these experiments characterize the fundamental cues available to cochlear implant users for making pitch judgements. The results suggest that temporal precision of stimulation has a large effect on the robustness and resolution of pitch perception provided by cochlear implant stimulation.

These findings are consistent with a growing body of literature that suggests that the temporal precision of acoustic/electric stimulation affects the salience of pitch perception and spatial hearing[47,48,57,58,49–56]. The results should be interpreted with caution when considering the categorical comparison between the use of pulse rate and modulation frequency of stimulation. The results indicate that pitch tends to be better provided by pulse rate than by modulation frequency when amplitude modulation is sinusoidally applied with 100% depth between comfortable stimulation levels and detection thresholds. Studies of pitch perception and spatial hearing in normal-hearing listeners have shown that modulation depth contributes to performance. It is possible that deeper modulations than considered here may result in comparable performance between pulse rate and modulation frequency.

The caution raised in the preceding paragraph is important to resolve for the design of the next generation of sound coding strategies for cochlear implants. Two styles of sound coding for cochlear implants have emerged that try to improve temporal coding of sound in different ways. First, some strategies trigger pulse timings based on the temporal features of the incoming sound. The PDT and FSP strategies described in the introduction are in this category as they trigger pulse timings based on the temporal fine structure of sound processed into frequency bands[40–45]. The Fundamental Asynchronous Stimulus Timing (FAST) strategy is also in this category as it triggers pulse timings in each frequency band based on maxima in the temporal envelope rather than the temporal fine structure[65,66]. In contrast, a second category of strategies try to improve temporal coding of sound by

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enhancing modulation of constant-rate stimulation[40,67,68]. Strategies such as HIRES, OPAL, and high-definition CIS all use constant stimulation rates but have unique algorithms for enhancing modulation depth and/or for controlling modulation synchrony across electrodes.

The present experiments suggest that a strategy that triggers pulse timings based on envelope periodicity may provide better pitch salience than one based on amplitude modulation. It is possible that envelope enhancement strategies need to provide modulations deeper than 100% modulation applied between comfort and detection thresholds. Modulating between comfort and threshold is not exceptionally deep in cochlear implant stimulation since the electrical dynamic range is typically small[9,69,70]. Modulating between comfort and true zero or using sharper modulations like half-wave rectified sinusoids might produce pitch resolution on par with using variable pulse rates. However, pushing the envelope in this manner, requiring temporally sharper envelope profiles would likely require higher stimulation rates to avoid distortion related to under sampling of the modulation envelopes.

While there are challenges for encoding deeper modulations with CIS-style envelope-coding strategies, there are also critical challenges for strategies based on triggering pulse timings for variable-rate stimulation. None of the cochlear implants available today allow for acoustically triggered simultaneous pulses to be delivered. While Advanced Bionics provides some technical capacity to trigger simultaneous pulses, doing so requires pulses to be predefined in a pulse table. All of the other clinically available cochlear implants only allow for sequential pulsatile stimulation with some dead time required between pulses. Consequently, variable-rate strategies that trigger pulse timings based on acoustic temporal-fine or temporal-envelope structure must employ pulse scheduling logic to avoid conflicts. Doing so necessarily results in pulses being dropped, which may lead to audible distortion.

Furthermore, for both styles of temporal enhancement, whether variable-rate or envelope enhancement, it is unknown to what extent timing information needs to be synchronized across electrodes or somehow matched to traveling-wave dynamics of natural physiology[71]. Consequently, the cochlear implant field has long struggled with issues related to providing better temporal coding for sound processing designed for multi-electrode stimulation. The experiments presented here circumvent these issues to examine pitch salience in the presence of interference using relatively straightforward electrode psychophysics. The results indicate that the precision of temporal stimulation matters, and that pulse rate provides a better sense of pitch compared to modulation frequency of constant-rate stimulation. It is important that future experiments examine the fundamental encoding of periodicity with both variable-rate stimulation and amplitude-modulation frequency with increasing realistic multi-electrode stimulation. Doing so will clarify the extent that better sound processing can be built for conveying temporal cues while avoiding distortion.

A limitation of the present study is that the small number of participants does not allow characterization of individual differences in sensitivity to modulation depth as a cue for pitch perception. The experiments described here use within-subject designs to reduce errors associated with individual differences and to test the main hypothesis that pitch is better conveyed by pulse rate than by modulation frequency. While that hypothesis tested true at the group level, further studies are needed to clarify individual differences associated with this effect. It is possible that cochlear implant users who are more sensitive to modulation, as measured by modulation detection thresholds, might also be able to perceive pitch differences associated with modulation frequency and not need the more precise temporal stimulation provided by pulse rate. Exploration of individual differences is beyond the scope of the present study, which provided evidence at the group level that pitch is better conveyed by pulse rate than by modulation frequency.

In conclusion, the experiments described in the present article tested two key hypotheses associated with providing cochlear implant users a robust and resolved sense of pitch; the results indicate that pitch is more robust and better resolved when provided by pulse rate than by modulation frequency (when the modulation is with 100% depth applied between comfort and threshold). The results have implications for the design of better sound processing for cochlear implants. Cochlear implants are exceptionally designed for conveying timing information and auditory physiology is exceptionally evolved for receiving timing information[72]. Sound processing for cochlear implants should take advantage of this exquisite temporal interface, and the evidence indicates that using variable pulse rates rather than modulation frequency can reduce temporal interference that arises from multi-electrode stimulation.

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Highlights

- Pitch discrimination is more robust when provided by cochlear implant stimulation rate than by amplitude modulation of constant stimulation rates.
- Pitch discrimination is also better resolved when provided by stimulation rate than by modulation frequency.
- The advantage of stimulation pulse rate compared to modulation frequency is most pronounced when electrical interference is spatially overlapping with the target stimulation.

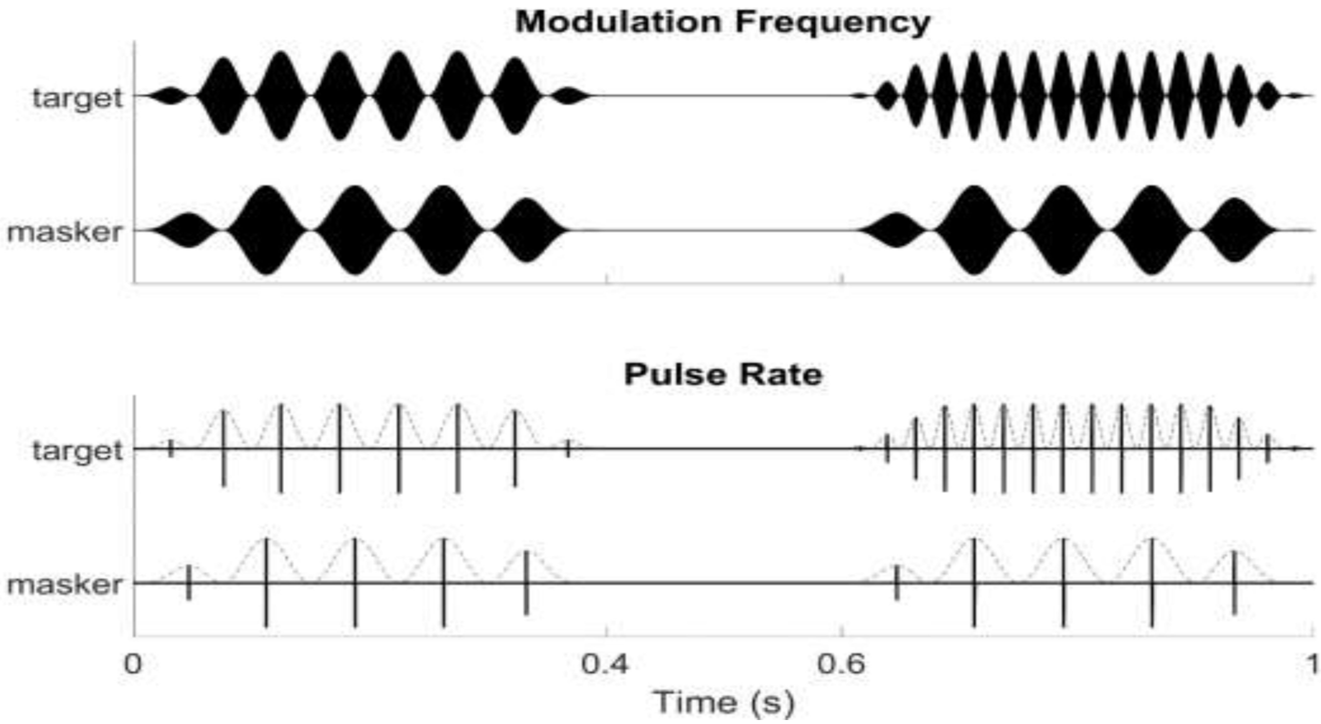

Figure 1:

Illustration of stimuli. The upper panel illustrates stimuli for conditions that tested pitch ranking provided by modulation frequency of constant-rate stimulation; the lower panel illustrates stimuli for conditions that tested pitch ranking provided by pulse rate. Modulation frequencies and pulse rates have been reduced here for ease of viewing. The dashed line in the lower subplot indicates the modulation envelope from the upper subplot for comparison.

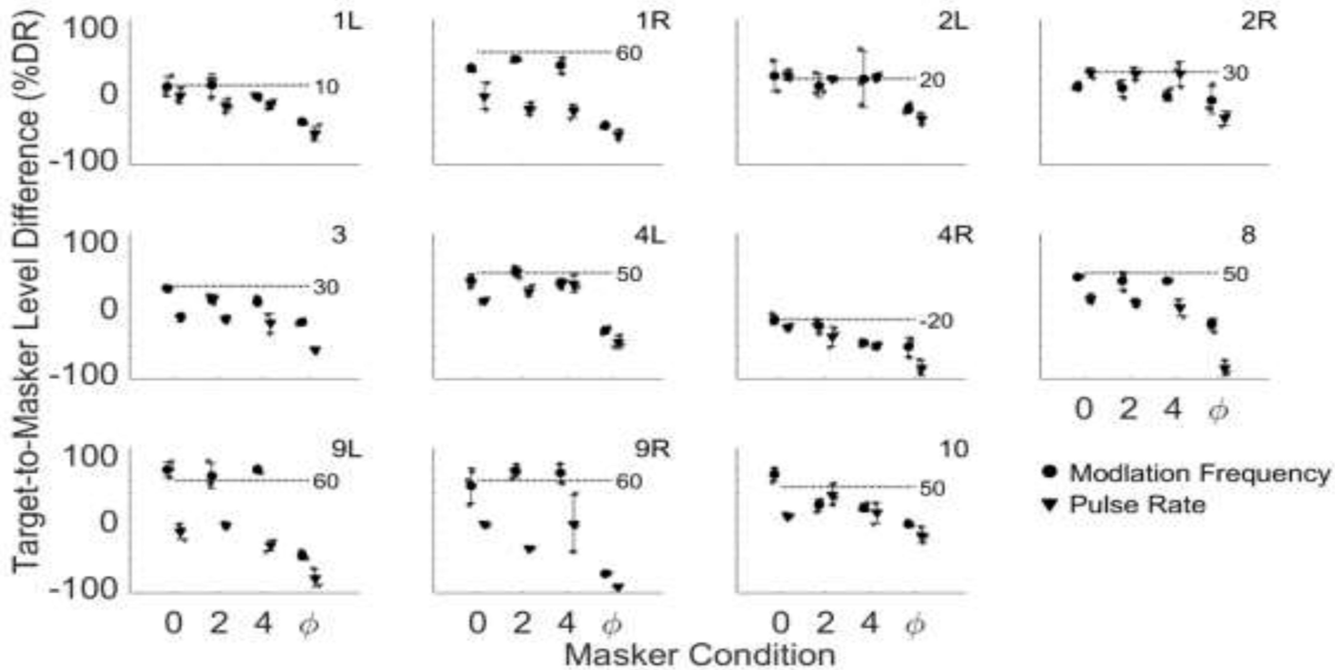

Figure 2:

Measured target-to-masker level differences needed for individual listeners to discriminate an octave difference in modulation frequency or pulse rate. Results are plotted as percent dynamic range with 100% corresponding to the target at comfort and the masker at threshold; 0% corresponding to both target and masker at comfort; and −100% corresponding to target at threshold and masker at comfort. Symbols indicate averages across measurement runs and error bars indicate standard deviations of the means. The masker conditions are labeled by spacing between target and masker with 0: masker co-located with target, 2: masker separated by 2 electrodes, 4: masker separated by 4 electrodes, and *Φ*: no masker.

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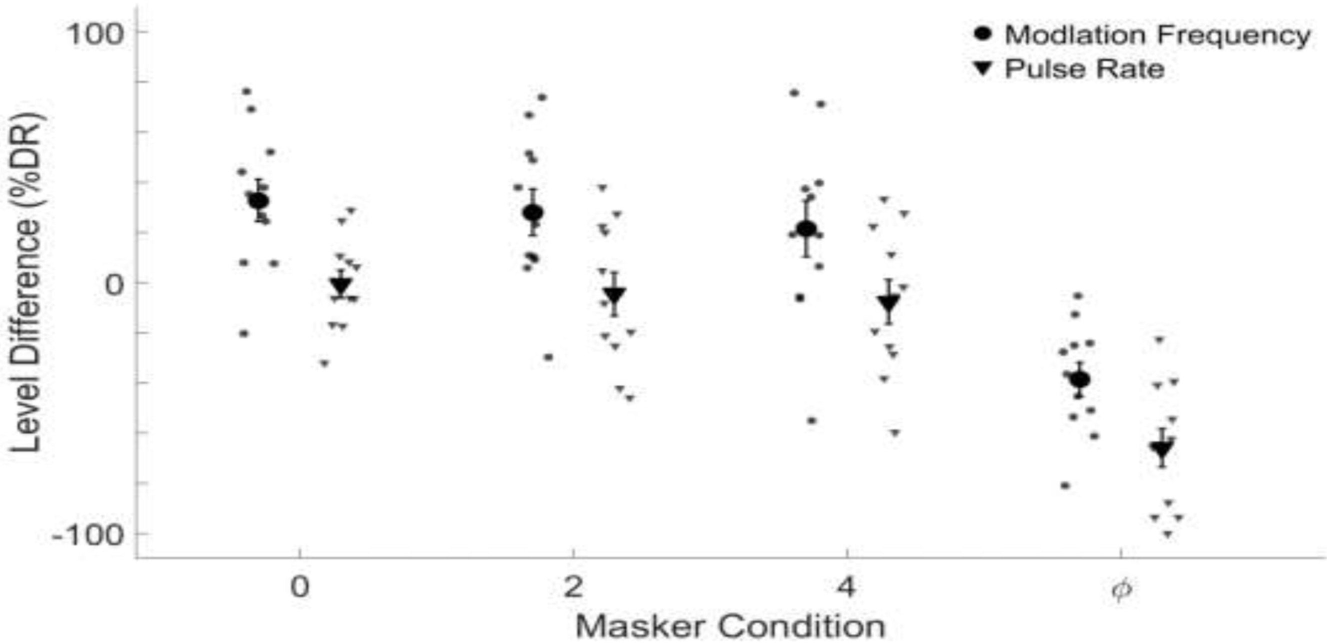

Figure 3:

Group averages and standard errors of the means for target-to-masker level differences needed to detect a one octave change in modulation frequency or pulse rate for each condition.

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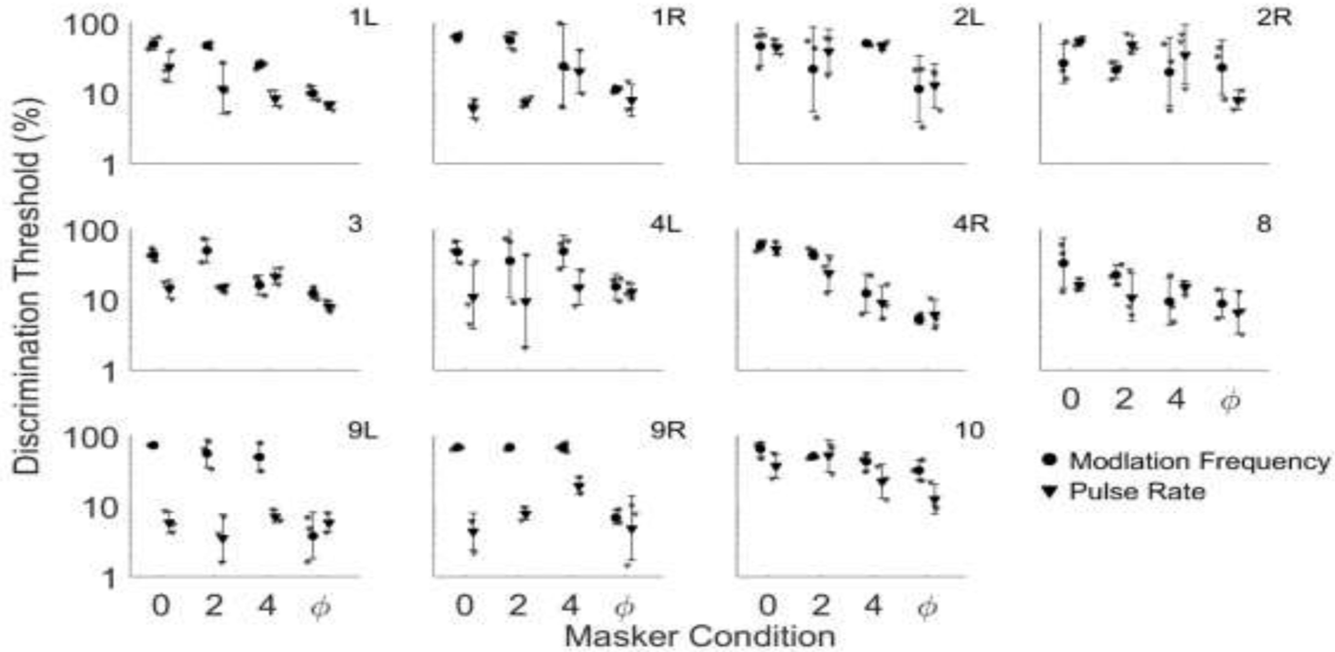

Figure 4:

Measured discrimination thresholds for individual listeners based on changes in modulation frequency or pulse rate. For conditions with a masker, the target-to-masker level difference was set based on the results of Experiment 1 as indicated in Figure 2. Symbols indicate averages across measurement runs and error bars indicate standard deviations of the means. The masker conditions are labeled by spacing between target and masker with 0: masker co-located with target, 2: masker separated by 2 electrodes, 4: masker separated by 4 electrodes, and *Φ*: no masker.

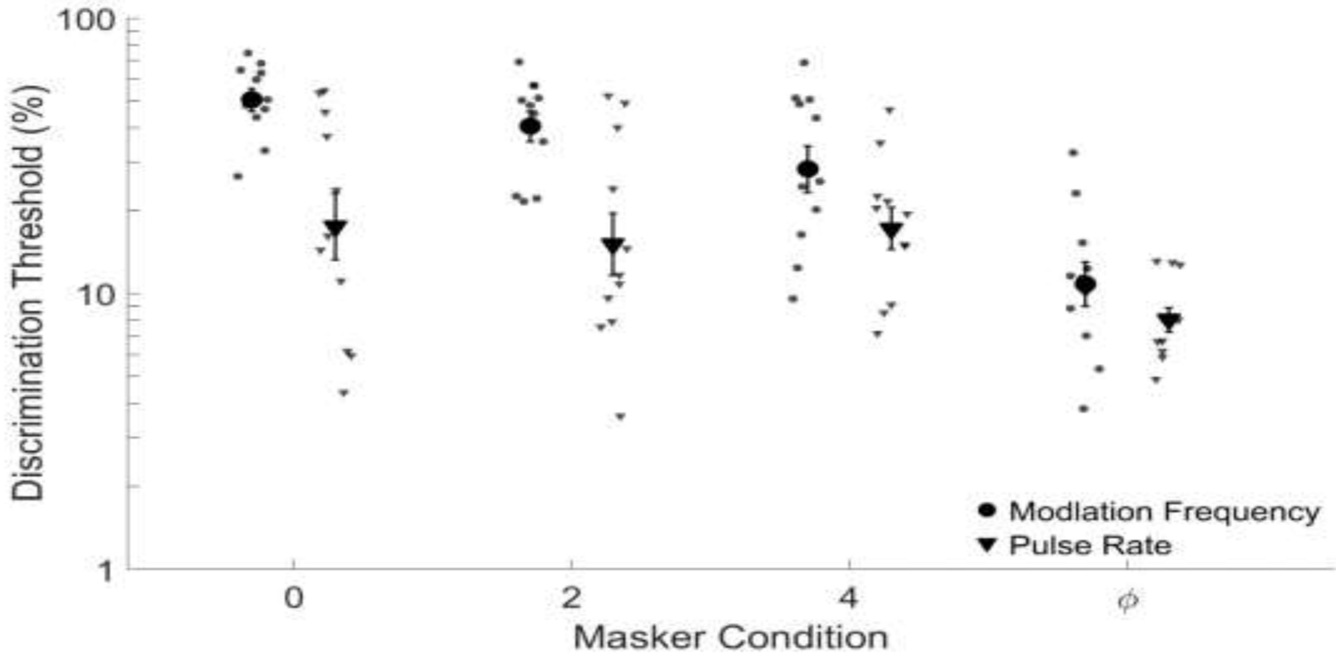

Figure 5:
Group averages and standard errors of the means for discrimination thresholds based on changes in modulation frequency or pulse rate.

TABLE 1.

Participant information.

Age at time of testing and age at onset of hearing loss is given in years. Duration of profound hearing loss in the implanted ear prior to implantation is given in years and estimated from subject interviews.

ID	Age	Gender	Etiology	Age at Onset	Years Implanted	Implant	Processor	Duration of Deafness
1	47	M	Meniere's	39	L: 1 R: 4	CI532 CI24RE (CA)	N7 N7	1 4
2	34	F	Unknown	15	L: 7 R: 11	CI24RE (CA) CI24RE (CA)	N7 N7	5 1
3	73	F	Progressive Nerve Loss	40	L: 18	CI24R (CS)	N6	1
4	58	M	Progressive Nerve Loss	Birth	L: 14 R: 1	CI24RE (CA) CI532	N7 N7	37 50
8	70	F	Sudden Nerve Loss	68	R: 2	CI1522	N7	1
9	72	M	Unknown	Birth	L: 1 R: 2	CI532 CI532	N7 N7	10 61
10	44	M	Meningitis	12	L: 31	CI22M-, USA	N6	1