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Combining Place and Rate of Stimulation Improves Frequency Discrimination in Cochlear Implant Users

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Abstract

In the auditory system, frequency is represented as tonotopic and temporal response properties of the auditory nerve. While these response properties are inextricably linked in normal hearing, cochlear implants can separately excite tonotopic location and temporal synchrony using different electrodes and stimulation rates, respectively. This separation allows for the investigation of the contributions of tonotopic and temporal cues for frequency discrimination. The present study examines frequency discrimination in adult cochlear implant users as conveyed by electrode position and stimulation rate, separately and combined. The working hypothesis is that frequency discrimination is better provided by place and rate cues combined compared to either cue alone. This hypothesis was tested in two experiments. In the first experiment, frequency discrimination needed for melodic contour identification was measured for frequencies near 100, 200, and 400 Hz using frequency allocation modeled after clinical processors. In the second experiment, frequency discrimination for pitch ranking was measured for frequencies between 100 and 1600 Hz using an experimental frequency allocation designed to provide better access to place cues. The results of both experiments indicate that frequency discrimination is better with place and rate cues combined than with either cue alone. These results clarify how signal processing for cochlear implants could better encode frequency into place and rate of electrical stimulation. Further, the results provide insight into the contributions of place and rate cues for pitch.

Keywords

Auditory neuroscience; Cochlear implant; Pitch; Psychophysics

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CRediT authorship contribution statement

Susan R.S. Bissmeyer: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Raymond L. Goldsworthy:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing.

Supplementary materials

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1. Introduction

Though cochlear implants have been widely successful, there are well-known deficiencies related to speech recognition and music appreciation. Pitch perception, essential for speech and music, is poorly provided by cochlear implants. Poor pitch resolution diminishes speech comprehension in background noise (Caldwell and Nittrouer, 2013; do Nascimento and Bevilacqua, 2005; Fu and Nogaki, 2005), vocal emotion recognition (Deroche et al., 2014; Gilbers et al., 2015; Luo et al., 2007), music appreciation (Bruns et al., 2016; Gfeller et al., 2000), and, consequently, quality of life (Ambert-Dahan et al., 2015; Lassaletta et al., 2008, 2007; Looi et al., 2012, 2008; Looi and She, 2010; Moran et al., 2016). Motivated by the essential role of pitch in hearing, the study described here considers psychophysical cues that support frequency discrimination in cochlear implant users.

In normal hearing, frequency is inseparably encoded in the tonotopic and temporal response properties of the auditory nerve. The tonotopic response to frequency, or place-frequency map, is initiated by mechanical tuning properties of the cochlea and persists throughout the ascending auditory pathway (Clopton et al., 1974; Fekete et al., 1984; Liberman, 1982; Muniak et al., 2016; Ryugo and May, 1993). The temporal response properties derive from the remarkable ability of the auditory nerve to phase-lock synchronously to acoustic frequencies as high as 5 kHz (van den Honert and Stypulkowski, 1987; Dynes and Delgutte, 1992; Dreyer and Delgutte, 2006; Hill et al., 1989; Shepherd and Javel, 1997; Rose et al., 1967; Palmer and Russell, 1986; Heinz et al., 2001). Although the auditory nerve can phase-lock to relatively high frequencies, there is active debate as to the upper limit of usable temporal frequency information for tasks such as sound localization, pitch perception, and speech perception (Verschooten et al., 2019). Because tonotopic and temporal cues are inseparable in normal hearing, there is debate regarding the contributions of these cues, as well as the possible need for aligning these cues synergistically (Attneave and Olson, 1971; Carlyon et al., 2012; Luo et al., 2012; McKay et al., 2000; Oxenham, 2013; Oxenham et al., 2011, 2004; Palmer and Russell, 1986; Rose et al., 1967). By whatever mechanism that tonotopic and temporal cues are decoded into a sense of pitch, normal hearing listeners can discriminate pure tones that differ by 1–5% in frequency for a wide range of frequencies (300–4000 Hz) with best discrimination near 0.1% (Goldsworthy et al., 2013; Micheyl et al., 2006; Tyler et al., 1983). Since tonotopic and temporal cues can be independently conveyed by cochlear implants, there are theoretical and practical motivations to measuring the contributions of these cues to pitch (Arnoldner et al., 2007; Laneau et al., 2004; Litvak et al., 2003; Oxenham et al., 2004; Shannon et al., 2004; Smith et al., 2002; Vermeire et al., 2010; Wilson et al., 2004).

Pitch perception provided by cochlear implant place-of-excitation has been studied using clinical processors and direct electric stimulation. The smallest discriminable difference in pitch between two frequencies is often measured as a discrimination threshold (measured in% difference from the base frequency for the present study). A single electrode will often have a quarter to one-third octave filter bandwidth with around 3–4 semitones allocated to each electrode (or 18.9–26% discrimination threshold for discriminating between single electrodes). Cochlear implant users can discriminate pure tones with their clinical processors that differ by between 1 and 30% across a wide range of frequencies (250–2000 Hz), with an average around 10%, an order of magnitude worse than normal hearing (Goldsworthy, 2015; Goldsworthy et al., 2013; Pretorius and Hanekom, 2008). Pure tone frequency discrimination through the clinical processor generally relies on place-of-excitation cues, but with the acknowledgement that some processing strategies, such as Fine Structure Processing (FSP) for MEDEL implants, may preserve temporal cues for low frequency pure tones. Computer-controlled electrode psychophysics, which bypass the clinical processor, allow specific place cues to be provided, but the stimuli may not be as familiar to the participant. Studies have shown tonotopic progression with basal electrodes heard as higher in pitch compared to apical electrodes (Nelson et al., 1995; Tong and Clark, 1985). Pairs of electrodes simultaneously stimulated or closely interleaved provide intermediate place cue percepts (Kwon and van den Honert, 2006; Landsberger and Srinivasan, 2009; Macherey and Carlyon, 2010; McDermott and McKay, 1994; Srinivasan et al., 2012). With this method, cochlear implant users can generally discriminate place-of-excitation differences of less than 1 electrode (Kenway et al., 2015; Laneau and Wouters, 2004; Townshend et al., 1987).

Studies have also examined the use of temporal cues for discriminating pitch (Bernstein and Oxenham, 2006; Houtsma and Smurzynski, 1990; Kaernbach and Bering, 2001; Shackleton and Carlyon, 1994). A semitone difference in Western musical notation is 5.95% from the base note frequency. Cochlear implant users can generally discriminate between harmonic complexes that differ by 5 to 30% for fundamental frequencies between 110 and 880 Hz, much worse than the 0.1 to 5% frequency resolution observed in normal hearing (Goldsworthy, 2015; Goldsworthy et al., 2013; Luo et al., 2019; Micheyl et al., 2006). The extent that this poor resolution is caused by degradation of tonotopic relative to temporal cues is unknown (Swanson et al., 2019). Studies that bypass clinical processing and test rate discrimination directly generally conclude that the temporal pitch mechanism is weak and unusable above 300 Hz (Carlyon et al., 2010; Laneau et al., 2004; Macherey and Carlyon, 2014; McDermott and McKay, 1997; McKay et al., 2000; Shannon, 1983; Tong et al., 1982; Tong and Clark, 1985; Zeng, 2002). However, since many clinical processors poorly encode temporal cues, it is possible that stimulation rate perception may require experience (Goldsworthy and Shannon, 2014; Wouters et al., 2015).

Mechanisms for decoding a sense of pitch based on stimulation rate have been put forth based on neural circuitry of the cochlear nucleus that receive inputs from broadly tuned regions of the auditory nerve (Bahmer and Langner, 2009; Golding and Oertel, 2012). This has led to speculation that multi-electrode stimulation with consistent timing information presented across the electrode array might provide better access to stimulation rate as a cue for pitch perception (Venter and Hanekom, 2014). The rationale was that the neural mechanisms of the cochlear nucleus would thus have better access to neural events across fibers, which would allow neural processing along the lines suggested by the Wever volley principle (Wever and Bray, 1937). Evidence for an advantage for multi-electrode compared to single-electrode stimulation has been mixed with some studies finding a small and consistent benefit of multi-electrode stimulation (Penninger et al., 2015; Venter and Hanekom, 2014), while other studies found no significant difference (Bahmer and Baumann, 2013; Carlyon et al., 2010; Laneau and Wouters, 2004; Marimuthu et al., 2016).

Hypothetically, place and rate cues for pitch may also be affected by the health of the auditory nerve. Forward-masked thresholds reflect multiple aspects of frequency tuning including electrode-neural geometry and local neural health (Bierer and Faulkner, 2010; Bissmeyer et al., 2020; McKay, 2012; Zhou, 2016). The present study aims to explore correlations of forward masking with pitch tasks to ascertain whether there is a relationship between an individual’s ability to discriminate pitch and their auditory neural health.

Studies have explored the combination of place and rate cues for pitch with varying results. Fearn and Wolfe (2000) implemented pitch scaling across electrodes and rates in which the subjects assigned a value on a numerical scale to the pitch of each stimulus considered, from 0 for very low pitch to 100 for very high pitch. They found that pitch perception was strongly a function of both cues, albeit with some saturation for more basally stimulated electrodes and marked saturation for rates above 500 pulses per second. Landsberger et al. (2016) looked at scaling pitch and quality for single-electrode stimulation in long-electrode arrays finding that different combinations of place and rate could produce similar pitch percepts but with different sound qualities. Schatzer et al. (2014) showed that the ability of single-sided deafened subjects to pitch match cochlear implant stimulation rates to a contralaterally presented acoustic pure tone of fixed frequency was better with apical electrodes for 100–300 Hz pure tones and basal electrodes for 450 Hz pure tones, while successful pitch matches could be made with medial electrodes across these pure tone frequencies (Landsberger et al., 2016). Rader et al. (2016) performed a similar experiment but with pitch matching acoustic pure tones to place dependent stimulation rates. They found very close acoustic to electrode frequency pitch matches in what they described as “unparalleled restoration of tonotopic pitch perception in CI users with single-sided deafness” and suggested that place dependent stimulation rates in CI signal processing could greatly improve pitch perception. Swanson et al. (2019) explored the contributions of place and rate to pitch percepts with judiciously chosen audio signals delivered through the clinical processor and found that rate and place could be used for pitch ranking and melody recognition, but that it could not be ruled out that melody recognition with place cues was perceived as brightness/timbre. Place and rate of stimulation have been posited to be perceptually orthogonal, in that both can be used to manipulate pitch percepts, but that they do not combine synergistically (Landsberger et al., 2018; Macherey et al., 2011; McKay et al., 2000; Tong et al., 1983). There is some evidence though that place and temporal pitch cues can be combined synergistically, though the mechanism of synergy is uncertain (Erfanian Saeedi et al., 2017; Luo et al., 2012; Rader et al., 2016; Stohl et al., 2008). Whether the place-rate integration is a fused synergy of the two cues for a single pitch percept or a perceptual weighting of the individual pitch dimensions for a pitch judgment, these four studies conclude that some combination of these two cues could improve signal processing strategies opening the window for better pitch perception in cochlear implant users.

The present study tests the primary hypothesis that combining stimulation place and rate improves frequency discrimination beyond either cue alone. In the first experiment, frequency discrimination needed to identify melodic contours was measured with place and rate cues, separately and combined. The frequency allocation used in Experiment 1 was modeled after the default allocation used on Cochlear Corporation devices. In the second experiment, a similar place-rate paradigm was used to test frequency discrimination needed for pitch ranking, with frequency allocation modified to improve access to low frequencies. Beyond the primary hypothesis that frequency discrimination is better provided by place and rate cues combined, we tested two secondary hypotheses that (1) broadness of stimulation could improve rate discrimination and (2) that auditory neural health as measured by forward masking has an effect on an individual's ability to perceive changes in pitch. The results clarify how place and rate cues combine to improve discrimination, which should inform developments in sound processing for cochlear implants.

2. Experiment 1: Melodic Contour Identification

2.1. General methods

2.1.1. Subjects—Seven cochlear implant users participated in this study. Four bilateral users were tested in each ear separately with the first ear tested randomly selected. All subjects were implanted with devices from Cochlear Corporation and were tested using the USC Cochlear Implant Research Interface which bypasses the clinical processor to provide precise control over stimulation parameters delivered directly through the implant (Shannon, 2015; Shannon et al., 1990). Relevant subject information is provided in Table 1. C9 had single-sided deafness until age 40 (their non-implanted ear information was provided for reference of post-lingual hearing). Participants provided informed consent and were paid for their participation. The University of Southern California's Institute Review Board approved the study.

2.1.2. Procedure—The threshold frequency difference that allows 75% identification accuracy for melodic contour identification was measured for place, rate, and combined place-rate cues. The primary hypothesis focused on testing whether melodic contour identification is better conveyed by combined place and rate of stimulation than by either cue alone. Melodic contour identification was measured using a one-interval, nine-alternative, forced-choice procedure. The nine melodic contours consisted of five-note patterns including "rising," "falling," "flat," "rising-flat," "falling-flat," "rising-falling," "falling-rising," "flat-rising," and "flat-falling" (Crew et al., 2012; Galvin et al., 2007). These nine contours of varying difficulty were presented an equal amount of times in pseudorandom order to measure overall realistic performance in an adaptive procedure (Galvin et al., 2007). Nine experimental conditions were tested including all combinations of three cue types (place, rate, and combined) and three center-note frequencies (100, 200, and 400 Hz) with the closest match to these center-note frequencies, based on Western music notation, being G2, G3, and G4. The rationale for testing such low frequencies was the similarity of place and temporal resolution, the self-reported best frequencies for cochlear implant user' music appreciation, and to probe performance at ecologically relevant fundamental frequencies of voicing which cross the range of the clinical filter bank. Conditions were repeated three times in random order. Correct-answer feedback was provided on all trials.

For each trial within a measurement run, the amplitudes of the five notes in the contour were randomly and independently roved between 90 and 100% (uniform distribution) of the width of the subject's dynamic range (in units of charge per phase—decibels re 1 ηCoulomb) as fitted by the logistic function. For each trial, the frequency of the third note of the five-note contour was roved within a quarter octave of the condition frequency; the third note did not change in the contours, so it was chosen for roving since the note frequencies were defined adaptively relative to the roved frequency of the third note. The purpose of frequency roving was to add perturbations which contribute to the ecological relevance of the stimulus (e.g., music played in different keys, vocal pitch fluctuations) while avoiding habituation to the third note frequency. The frequency spacing between notes in the melodic contour was adaptively controlled based on performance in this identification task. Both the adaptive ceiling and the initial frequency spacing between notes were 100% so that the greatest possible difference between notes would be an octave; the internote frequency spacing for identification was decreased by a factor of $\sqrt[3]{2}$ following correct answers and increased by a factor of 2 following mistakes. This adaptive rule keeps the internote frequency spacing at a difficulty level such that the procedure converges to 75% identification accuracy, or percent correct (Kaernbach, 1991). A measurement run continued until 12 mistakes were made and the internote threshold was calculated as the average frequency spacing of the last 8 reversals.

2.1.3. Loudness balancing—Detection thresholds and comfortable stimulation levels were measured as a function of stimulation rate to provide loudness balancing for procedures across electrodes and rates (Bissmeyer et al., 2020; Goldsworthy et al., 2022, 2021). These levels were measured in monopolar stimulation mode using a method of adjustment. Subjects used a graphical user interface (see Supplementary Fig. 1) with sliders to control and set the threshold and comfort levels for each of the eight stimulation rates, from 50 to 6400 Hz in octave intervals. Upon adjusting the slider, the subject would hear a change in amplitude for a 400 ms pulse train comprised of biphasic pulses with 25 μs phase durations and 8 μs interphase gaps. This pulse shape was designed to provide the necessary charge for stimulation over a brief phase duration. The chosen phase duration corresponds to typical clinical processor settings, and the maximum amplitude was 255 clinical units as defined by Cochlear Corporation. Subjects were instructed to adjust stimulation level for detection thresholds and for comfortable levels. The resulting detection thresholds and comfort levels were fit with a logistic equation of the form:

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

where U and L are the upper and lower limits of the subject's dynamic range (converted from clinical units to units of charge per phase), Q is related to the current level at 100 Hz, B is the rate by which the current decreases over the frequency range, x is frequency expressed as $\log_2$ (frequency/100), and v controls asymptotic growth. Fitted logistic equations were used to balance loudness for all stimuli used in the experiment.

2.1.4. Stimuli—The internote frequency spacing needed to support melodic contour identification (MCI) was measured using multi-electrode stimuli. Stimuli were generated by filtering pure tones through a filter bank with output envelopes used to define place, rate, and place-rate stimulation patterns. Melodic contours were defined as 5-note sequences of pure tones with tones defined as 200 ms sinusoids with 100 ms raised-cosine attack and release ramps. The slow attack and release times were used to promote a gradual recruitment of neurons to avoid hyper-synchronization to the first pulse (Carlyon and Deeks, 2015, 2013; Hughes et al., 2014, 2012; Hughes and Laurello, 2017). Sequences were filtered through a 4th-order, 22-channel, filter bank. The filter bank used logarithmic frequency allocation with quarter-octave spacing from 200 to 6400 Hz. This logarithmic filter bank was modelled after the quasi-logarithmic frequency allocation table used with Cochlear Corporation devices. Filtered outputs were converted to channel envelopes using a Hilbert transform. An "N-of-M" algorithm was used to select the 3 channels with the most energy. The output envelopes were then used to control constant-rate pulse trains comprised of pulses that were 25 μs in phase duration with 8 μs interphase gaps with stimulation rate experimentally controlled to provide place, rate, and combined place-rate cues for the frequencies used in the melodic contour. Example stimuli are shown in Fig. 1.

2.1.5. Analyses—The primary hypothesis tested is that frequency discrimination for melodic contour identification is better with combined place and rate of stimulation than with either cue alone. The collected data consisted of 3 repetitions of 9 conditions (3 stimulation cue types crossed with 3 center-note frequencies). Hypotheses were tested using a two-way repeated measures analysis of variance with stimulation cue and condition frequency as within-subject factors. All statistics were calculated on logarithmically transformed thresholds to be consistent with the underlying perceptual scale in frequency discrimination and the use of multi-plicative (rather than additive) steps in the adaptive logic (Micheyl et al., 2006). Planned multiple comparisons were used to quantify the effect of cue type at each frequency. Cohen's d was used as a measure of effect size (Cohen, 1992).

2.2. Results

No clear trends emerged in the participants' performance in the up-down procedure. With 12 mistakes necessary to finish a run, there were an average of 39.1 trials per run with a standard deviation of 15.6 trials, and with the longest run being 63 trials long. Average internote frequency spacing across all conditions including subject was 35.1% with a standard deviation of 2.5%. Fig. 2 shows internote frequency spacing thresholds needed to support melodic contour identification with place, rate, and combined place-rate cues. These internote frequency spacing thresholds are a function of the percent difference from the base note frequency. Frequency spacing thresholds were better with combined place and rate of stimulation than with either cue alone. Cue type was significant ($F_{(2,20)} = 17.17$, $p < 0.001$) with across frequency averages of 52.8% for place, 38.6% for rate, and 22.7% for combined cues. The corresponding comparisons of effect size were large and significant when comparing thresholds with combined cues with either cue alone ($d_{Cohen} > 0.6$, *both comparisons*). As a main effect, frequency was not significant ($F_{(2,20)} = 1.13$, $p = 0.34$), reflecting that internote frequency spacing averaged across cue type changed little with averages of 34.3% at 100 Hz, 39.9% at 200 Hz, and 34.0% at 400 Hz. Clearly, though, the salience of the cue changed with frequency, as manifested as a significant interaction between cue type and frequency ($F_{(4,40)} = 12.78$, $p < 0.001$).

Fig. 2 shows the tradeoff in performance between place and rate with poor place resolution at lower frequencies and worsening rate resolution at higher frequencies. The poor place resolution reflects the reduced filter spacing near 100 and 200 Hz. The worsening rate resolution at 400 Hz is balanced by an improved place resolution at that frequency. This tradeoff allows for the flat performance from combined place-rate cues as a function of frequency. Planned multiple comparisons were conducted to test the hypothesis that the combined cue performance was better than either cue alone at each condition frequency. This analysis indicated that only for the 200 Hz condition was the combined cue performance significantly better than either cue alone (place, $p < 0.001$; rate, $p = 0.0135$); for the 100 and 400 Hz conditions, the combined cue performance was not significantly better than the stronger cue (rate, $p = 0.72$ at 100 Hz; place, $p = 0.21$ at 400 Hz). So, while performance with combined cues was better than either cue alone as a main effect, performance was often driven by the stronger of the two cues.

Fig. 3 shows individual performance on melodic contour identification. Most subjects were able to perform this task but with substantial variability across subjects and even across ears in bilateral implant users. Only two subjects had a consistent benefit from combined cues for all frequencies (2R and 9). These results provide insight into individual differences using combined cues for melodic contour identification; for example, some implant users received a combined benefit at 400 Hz at a frequency where the ability to use rate for melodic contour identification is relatively poor (2L, 2R, 5, and 9), while one subject appeared to be confounded by poor rate resolution as combined performance was poorer than for the place cue alone at 400 Hz (1R). Most subjects at 400 Hz had combined cue performance consistent with their performance with place cues alone (1L, 3L, 3R, 4L, 4R, and 8). For the bilateral subjects (1–4), Subjects 3 and 4 exhibited markedly different performance between ears, with one ear performing relatively well and the other ear performing near ceiling, while Subjects 1 and 2 demonstrated similar performance between their respective ears.

3. Experiment 2: Frequency Discrimination

3.1. General methods

3.1.1. Subjects—The same subjects were tested as in Experiment 1.

3.1.2. Procedure—Frequency discrimination was measured using a two-interval, two-alternative, forced-choice procedure in which subjects were asked which interval was higher in pitch. The condition frequencies were 100, 200, 400, 800, and 1600 Hz for single and multi-electrode stimulation. The primary hypothesis focused on testing whether frequency discrimination is better provided by combined place and rate of stimulation than by either cue alone. This was tested with place, rate, and place-rate stimuli, with the focus of comparing place and rate separately to the combined place-rate stimulation. There were 15 multi-electrode conditions comprised of all combinations of the 3 types of stimuli (place, rate, and combined place-rate) at the 5 test frequencies. To explore the secondary hypothesis of broad stimulation improving rate discrimination, 5 single-electrode conditions with rate only for the 5 test frequencies were tested to be compared to the multi-electrode rate stimulus at the 5 test frequencies. Conditions were repeated three times in random order. Correct-answer feedback was provided on all trials.

For each trial within a measurement run, the amplitudes of the standard and target were randomly and independently roved in the same manner as Experiment 1. For each trial, the frequency of the standard was roved within a quarter octave of the condition frequency; the target frequency was defined adaptively higher relative to the roved standard frequency. The initial difference that the target frequency was higher than the standard frequency was 64% with an adaptive ceiling of 128% frequency difference. The difference for discrimination was decreased by a factor of $\sqrt[3]{2}$ after correct answers and increased by a factor of 2 after mistakes. This adaptive rule keeps the frequency spacing for discrimination at a difficulty level such that the procedure which converges to 75% correct, (Kaernbach, 1991). The procedure continued until the participant made 10 mistakes and the discrimination threshold was calculated as the average of the last 8 reversals.

3.1.3. Loudness balancing—The detection threshold and comfort levels from Experiment 1 were used to balance loudness in the same manner.

3.1.4. Stimuli—Frequency discrimination for pitch ranking was measured for loudness balanced single and multi-electrode stimuli. Stimuli were created as described for Experiment 1 but with key differences meant to improve place resolution at the lower frequencies. This was done by filtering a pure tone through a filter bank and using the output envelopes to scale constant-rate pulse trains. The pure tones were 400 ms sinusoids with 200 ms raised-cosine attack and release ramps. Tones were filtered through a 22-channel filter bank comprised of second-order filters logarithmically spaced one-third octave apart with center frequencies from 50 to 6400 Hz. This filter spacing was modified from the frequency allocation similar to that which is used with Cochlear Corporation devices to provide better place coding of frequencies below 200 Hz. Since participants were given no acclimation period to these programming changes, we chose to use a simple pitch ranking task to measure frequency discrimination. Filtered outputs were converted to channel envelopes using a Hilbert transform. A second processing difference from Experiment 1 was that the “N-of-M” algorithm was used to select the 5 channels (for the multi-electrode conditions), rather than 3 channels, with the most energy to explore the potential benefit of broader stimulation. Similar to Experiment 1, these envelopes were used to modulate constant-rate pulse trains comprised of pulses that were 25 μs in phase duration with 8 μs interphase gaps. The rate of the constant-rate pulse trains was experimentally controlled depending on the condition. For the single-electrode rate only condition, the channel with the most peak energy was used for stimulation. Example stimuli are shown in Fig. 4.

3.1.5. Analyses—The primary hypothesis tested is that frequency discrimination is better provided by combined place and rate of stimulation than by either cue alone. Each subject completed 3 repetitions of 15 conditions consisting of every combination of stimulation cue (place, rate, combined) and condition frequency (100, 200, 400, 800, 1600 Hz). A two-way repeated measures analysis of variance (ANOVA) with interactions was conducted with cue type and frequency as within-subject factors. All statistics were calculated on logarithmically transformed thresholds (Micheyl et al., 2006). Planned multiple comparisons were conducted to examine the effect of cue type at each frequency. Cohen's d was used as a measure of effect size (Cohen, 1992).

A secondary hypothesis tested is that consistent stimulation rates provided on multiple electrodes can improve rate discrimination over that with single-electrode stimulation, with the rationale that consistent rates on multiple electrodes could improve rate discrimination. Each subject completed 3 repetitions of stimulation rate discrimination for 10 conditions consisting of 2 stimulation configurations (single, multi) and 5 condition frequencies (100, 200, 400, 800, 1600 Hz). A two-way repeated measures ANOVA was conducted with stimulation configuration and frequency as within-subject factors. Planned multiple comparisons were conducted to test the effect of stimulation configuration at each frequency.

Correlation analysis was conducted between the measures of frequency discrimination with forward-masked thresholds reported in a previous study (Bissmeyer et al., 2020). Forward-masked thresholds were measured as the probe detection threshold on a set of electrodes, 0,1, 2, and 4 electrodes away from the masker, presented at a comfortable level. The metric of frequency tuning based on forward-masked detection was calculated as the slope of the thresholds across these electrodes. Five of the participants from the present study (4 of whom were bilateral) took part in Bissmeyer et al. (2020), and the reported metric of frequency tuning based on forward-masked detection was tested for correlation with the frequency discrimination thresholds measured by pitch ranking reported in the present study. The hypothesis was that an individual's ability to discriminate pitch would be affected their auditory neural health, as measured by forward masking. Correlation analysis was conducted between monopolar forward-masked thresholds averaged across apical and basal testing sites and frequency discrimination thresholds averaged across frequency.

3.2. Results

No clear trends emerged in the participants' performance in the up-down procedure. With 10 mistakes necessary to complete a run, there were an average of 40.1 trials per run with a standard deviation of 10.7 trials, and with the longest run being 60 trials long. Average frequency discrimination across all conditions including subject was 15.4% with a standard deviation of 3.2%. Fig. 5 shows the benefit of combining place and rate cues compared to place or rate cues alone. Average discrimination was better with combined place and rate cues than with either cue alone ($F_{(2,20)} = 26.91$, $p < 0.001$). The grand means for stimulation cue averaged across frequency were 18.4% for place, 19.6% for rate, and 9.0% for the combined cue conditions. This benefit of the combined cue condition was large and significant when compared to place or rate alone ($d_{Cohen} > 0.7$, *both comparisons*).

As shown in Fig. 5, rate discrimination thresholds exhibit the characteristic trend of worsening for higher rates. In contrast, place discrimination is relatively flat but with an average best performance near 400 Hz, which corresponds to a location near electrode 8 for the frequency allocation used in this experiment. Discrimination for the combined cue condition tracks the better of the two cues with a significant and synergistic improvement measured for the 100, 200, and 400 Hz conditions. These observations were statistically confirmed with a clear effect of frequency on discrimination thresholds with worsening thresholds for higher frequencies ($F_{(4,40)}$ = 22.18, $p < 0.001$), and there was a significant interaction between stimulation cue and frequency ($F_{(8,80)}$ = 14.79, $p < 0.001$).

Planned multiple comparisons were calculated to test the hypothesis that the combined cue would provide better discrimination over either cue alone for each frequency. The multiple comparisons test was conducted with Fisher's least significant difference. Measured discrimination thresholds were significantly better for the combined cue than for either cue alone for the 100 (place, $p < 0.001$; rate, $p = 0.02$), 200 (place, $p < 0.001$), and 400 (place, $p = 0.047$; rate, $p = 0.0055$) Hz conditions, except for rate discrimination at 200 Hz not reaching significance ($p = 0.074$). The effect sizes of these comparisons were large ($d_{Cohen} > 0.4$). For the 800 and 1600 Hz conditions, rate discrimination was significantly worse than for the combined cue condition ($p < 0.001$), and place discrimination was not significantly different from the combined cue condition ($p = 0.38$ and $p = 0.59$, respectively). Place and rate discrimination were significantly different for all frequencies ($p < 0.01$) except for 400 Hz ($p = 0.14$), with the stronger cue switching between 200 and 400 Hz.

Fig. 6 plots individual discrimination demonstrating that performance is highly variable. For rate cues, some implant users struggle above 200 Hz (e.g., 4L), while others have discrimination resolution better than 10% for frequencies up to 800 Hz (e.g., 1R). For place cues, some implant users struggle with electrode discrimination and their performance is consistently poor (e.g., 3R), while others are consistently flat hovering around 15% discrimination (e.g., 1 L). These results provide insight into individual benefit from combined cues; for example, some implant users receive a benefit at 1600 Hz at a frequency where rate discrimination is relatively poor (3L, 3R, 4L, 5, and 9), while others appear to be confounded by the poor rate cue and combined performance is worse for the place cue alone at 1600 Hz (1R, 2L, 4R, and 8).

Considering differences across ears within the same participant, Subject 1L had a place-rate benefit from 200 to 800 Hz over either cue alone while 1R did not have a significant place-rate benefit for any frequency. Subject 4 is the only bilateral user who had similar performance across ears and, interestingly, had poor use of place and rate cues at higher frequencies. Each participant, and sometimes the same participant across ears, receive varying benefits from different cues.

In Fig. 7, we explore the secondary hypothesis of whether rate discrimination is better with multi-electrode than with single-electrode stimulation. The results show that the effect of stimulation configuration was significant ($F_{(1,10)}$ = 22.2, $p < 0.001$), with single-electrode rate discrimination averaged across frequency (14.2%) significantly better than multi-electrode rate discrimination (19.6%) ($d_{Cohen} = 0.27$). The effect of stimulation rate was significant ($F_{(4,40)}$ = 32.1, $p < 0.001$), reflecting the well-established deterioration of discrimination for increasing rates. The interaction between stimulation configuration and rate was not significant ($F_{(4,40)}$ = 1.6, $p = 0.19$), reflecting the similar trend as a function of frequency after adjusting for mean differences.

Planned multiple comparisons were calculated to test the significance of stimulation configuration for each frequency with Fisher's least significant difference. Measured discrimination thresholds were significantly better with single-electrode than with multi-electrode stimulation for the 100 (p = 0.004), 400 (p = 0.038), and 800 (p = 0.0025) Hz conditions. The effect sizes of these comparisons were large (d_{Cohen} > 0.4, *all comparisons*).

Forward-masked detection thresholds were examined to test the hypothesis that degradations in frequency tuning—reflecting electrode-neural geometry, local neural health, and tonotopic pitch associated with different places of excitation—affect temporal and tonotopic pitch mechanisms (Bierer and Faulkner, 2010; Bissmeyer et al., 2020; McKay, 2012; Zhou, 2016; Zhou et al., 2019). Fig. 8 shows the correlation of forward-masked slopes, see methods in Bissmeyer et al. (2020), with frequency discrimination for the subset of 5 overlapping subjects in the present study (1–5) for all stimulation cues (place, rate, place-rate, and single-electrode rate). Frequency discrimination based on place cues yielded a weakly significant positive correlation (p = 0.053) indicating better than average place discrimination for steeper than average forward-masked slopes. The correlations for rate (p = 0.008), place-rate (p = 0.017), and single-electrode rate (p = 0.004) were significant, likewise indicating better discrimination for steeper forward-masked slopes. The consistent trend across correlations was that steeper forward-masked slopes, or sharper frequency tuning, correlated with better than average frequency discrimination.

A correlation between performance on Experiments 1 and 2 was done to explore whether those who performed better at simple frequency discrimination also performed better at melodic contour identification. The position correlation indicating better performance on one task was predictive of the other held up for the place cue only (p = 0.062) albeit insignificantly, rate cue only (p = 0.037), combined place-rate cue (p = 0.029), and performance averaged across the cue conditions (p = 0.011). Correlations were also explored for place cue vs rate cue performance for both experiments to explore any individualized preference for tonotopic vs temporal cues. Albeit insignificant, a positive trending correlation was found with subjects performing better at tonotopic cues also performing better with temporal cues for both frequency discrimination (p = 0.25) and melodic contour identification (p = 0.21).

The performance at both experiments was then correlated with age, duration of deafness before implantation and duration of cochlear implant experience. Fig. 9 shows the 2 correlations which reached or neared significance, as well as the corresponding pairs to these correlations which did not. Melodic contour identification based on rate cues yielded a significant positive correlation with duration of cochlear implant experience (p = 0.034) indicating better than average place discrimination for steeper than average forward-masked slopes. Frequency discrimination based on rate cues reached a near significant positive correlation with duration of deafness before implantation (p = 0.058). Neither melodic contour identification correlated with duration of deafness before implantation (p = 0.63) nor frequency discrimination correlated with duration of cochlear implant experience (p = 0.39) reached significance but were plotted to demonstrate the positive but insignificant pairing to the significant correlations. The consistent trend across correlations was that rate discrimination is better for shorter duration of deafness before implantation and for shorter duration of CI experience. One possibility is that those who have longer durations of implantation may be less sensitive to temporal cues since the processor does not encode temporal fine structure.

4. Discussion

The primary hypothesis tested by the experiments described here is that coordinated use of place and rate of stimulation can enhance frequency discrimination for cochlear implant users. This hypothesis was substantiated in both experiments with significant improvements observed with combined place and rate of stimulation. That coordinated use of place and rate can improve basic frequency discrimination as well as melodic contour identification motivates careful consideration of how these cues are provided by cochlear implants. A secondary hypothesis was tested in Experiment 2, that multi-electrode stimulation provides better access to stimulation rate cues compared to single-electrode stimulation. The evidence indicates the contrary, that single-electrode stimulation provides better rate discrimination. Discussion focuses on the clinical implications of these two findings.

4.1. Coordinated place and rate of stimulation for cochlear implants

Cochlear implant users hear a sense of pitch associated with both place and rate of stimulation. Place of stimulation makes use of the basic tonotopy of the auditory system with more deeply implanted electrodes typically evoking lower pitch percepts. In clinical programming, the way acoustic frequency is allocated to electrodes is flexible. Different manufacturers use different rules for frequency allocation and audiologists may tailor allocation for individuals. The default frequency allocation for Cochlear Corporation devices uses a lower frequency edge of 188 Hz with center frequencies of filters spaced 125 Hz apart until the middle of the array at which point transitioning to quasi-logarithmic spacing. With such spacing, only the most apical electrode is allocated to the region representing the typical range of fundamental frequencies of spoken speech in adults. The default frequency allocation for Advanced Bionics devices uses logarithmic spacing with a lower frequency edge of 333 Hz. A rationale for providing little or no frequency allocation below 333 Hz is that fundamental frequencies of speech will manifest in the temporal envelopes extracted from each band. However, few studies have considered the extent that a dense frequency allocation in the range of fundamental frequencies for spoken speech might improve pitch perception (Geurts and Wouters, 2004).

In the present study, Experiment 1 considered frequency allocation similar to Cochlear Corporation devices, while Experiment 2 considered a denser frequency allocation with logarithmically spaced filters from 50 to 6400 Hz with one-third octave spacing providing more resolution in the lower frequencies. With the spacing in Experiment 2, participants could, on average, discriminate pitch changes of about 15% based on changes in place of stimulation. This is remarkable since the experiment was a short-term experiment without familiarization to this cue. The tradeoff that must be considered, though, is the extent that increasing the density of allocation to low frequencies in the voice pitch range reduces the density of allocation of higher frequencies in the range of formant frequencies. It is difficult to explore this tradeoff because frequency allocation is such a basic element of cochlear implant programming that modifying it can require months to adjust to depending on the extent of the changes. Longitudinal systematic studies of allocation are needed.

Stimulation rate, whether as modulation rate or as variable pulse rate, also evokes a consistent sense of pitch for cochlear implant users. Most cochlear implants use modulation rates of constant-rate pulsatile stimulation to convey periodicity cues for pitch, though some strategies use stimulation that is triggered by phase locking stimulation to the temporal fine structure of sound in each frequency band (Arnoldner et al., 2007; van Hoesel and Tyler, 2003; Wouters et al., 2015). The provision of this temporal information does not covary with place of stimulation in existing cochlear implants. Specifically, the place and rate of stimulation is not coordinated such that higher frequencies cause both an increase in modulation rate and a basal shift in stimulation place (Arnoldner et al., 2007; Riss et al., 2014). Instead, the rate of stimulation is like that of normal hearing when listening to unresolved harmonics, where only temporal cues are available for pitch (Moore and Carlyon, 2005; Swanson et al., 2019). Evidence clearly indicates that pitch resolution is better provided in normal hearing when covarying place and rate cues are provided for low-numbered, tonotopically resolved, harmonics (Bernstein and Oxenham, 2006; Houtsma and Smurzynski, 1990; Kaernbach and Bering, 2001; Shackleton and Carlyon, 1994).

The results of the present experiments indicate that stimulation rate provides a robust cue for detecting pitch changes at least up to 400 Hz. Discrimination of pitch changes based on stimulation rate was, on average, better than 10% when tested near 100 and 200 Hz but degraded to about 20% near 400 Hz. The combined use of place and rate of stimulation provided better frequency discrimination than either cue alone for these frequencies; however, discrimination with the combined cue was generally only marginally better than with the stronger of the two cues. This finding suggests that optimal encoding of place and rate cues would benefit from detailed and individualized characterization of cue strength. Such an optimization might follow the approach presented here but with familiarization to the jointly encoded place-rate cues. The familiarization process is important since there is clear evidence of rehabilitative plasticity associated with both place and rate of stimulation (Goldsworthy and Shannon, 2014; Reiss et al., 2014).

4.2. Does broad stimulation provide better access to rate pitch cues?

The present study included a component in Experiment 2 that directly compared rate discrimination with multi-electrode and single-electrode stimulation. Contrary to the argument for multi-electrode stimulation, the results presented here indicate a small but significant advantage for single-electrode stimulation. Our interpretation of this finding is that single-electrode stimulation is temporally more precise since it avoids the smearing of temporal information that necessarily must occur with Cochlear Corporation devices, which require a 12 μs delay between pulses across electrodes (Boulet et al., 2016). Stimulation used in the present study was presented base to apex, so would have been grossly consistent with physiological compensatory mechanisms for delay, but, in the described experiment, delays were not tailored to cochlear delays of characteristic frequencies estimated from electrode positions. It is possible that the sense of pitch provided by stimulation rate using multiple electrodes could be optimized by tailoring the stimulus delay either psychophysically or by physiological estimates. This, however, is speculation and it may well be that the physiological compensatory mechanisms may not exist for cochlear implant users who do not receiving the traveling wave through their processor.

We further postulate that any need for stimulating broad regions of the auditory nerve to provide sufficient across fiber excitations for upstream decoding to take place is already provided by the broad stimulation patterns that occur for a single-electrode using monopolar stimulation (Middlebrooks and Snyder, 2010). This is supported by the observed correlation of forward-masked threshold slopes with frequency discrimination indicating better place and rate discrimination with narrower fields of stimulation as quantified by steeper forward-masked slopes. That better rate discrimination was positively correlated with steeper forward-masked slopes suggests that both single and multi-electrode stimulation are broad enough to provide across fiber comparisons for upstream decoding, with narrower stimulation providing an advantage because it avoids unnecessary temporal smearing. That better place discrimination was positively correlated with steeper forward-masked slopes suggests that place-pitch judgements partially depend on comparisons of the overall excitation pattern and not simply the centroid of the response. The small but consistent benefit for single-electrode compared to multi-electrode stimulation for rate discrimination highlights how a relatively narrow field of stimulation may provide better frequency access to both place and rate cues for cochlear implant users.

5. Conclusions

Two experiments were described that examined the sense of pitch conveyed by electrode position and stimulation rate, separately and combined, for cochlear implant users. Results indicate that frequency discrimination was generally better with place and rate cues combined than with either cue alone; however, resolution was often dominated by the stronger of the two cues. A synergistic benefit of combined cues was measured up to 400 Hz for the simple frequency discrimination task. It remains unknown to what extent covarying stimulation place and rate in clinical devices could lead to long-term benefits after optimizing frequency allocation and providing familiarization to the newly encoded information.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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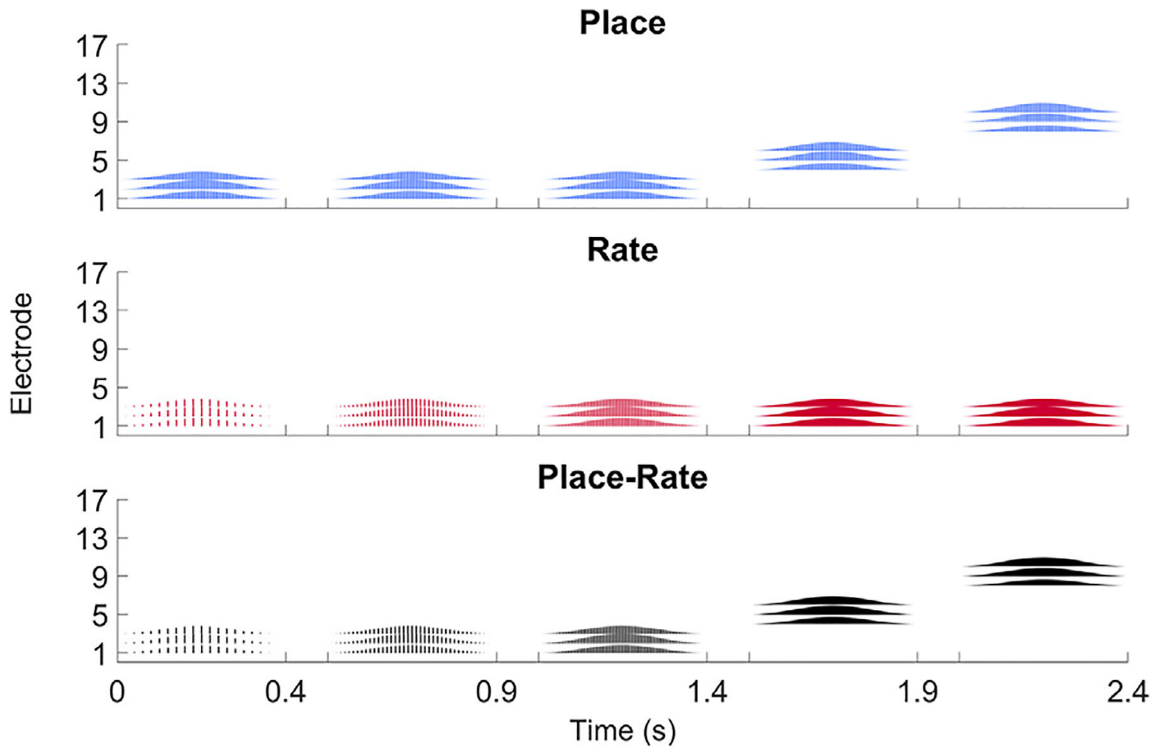

Fig. 1.
Example stimuli for experimental conditions of place, rate, and combined place-rate. The melodic contour is "rising", but the frequency allocation table used for the melodic contour identification task, modeled after the frequency allocation for typical Cochlear Corporation devices, has a cutoff of 200 Hz limiting the place information at the lower frequencies and making it look more like the "flat-rising" contour for place-of-excitation cues. The first panel shows the condition where place of stimulation is varied, and rate is held constant at the center-note frequency. The second panel shows the condition where rate of stimulation is varied, and place of stimulation is held constant at the center-note frequency. The third panel shows the combined place-rate condition with both place and rate covaried for all notes.

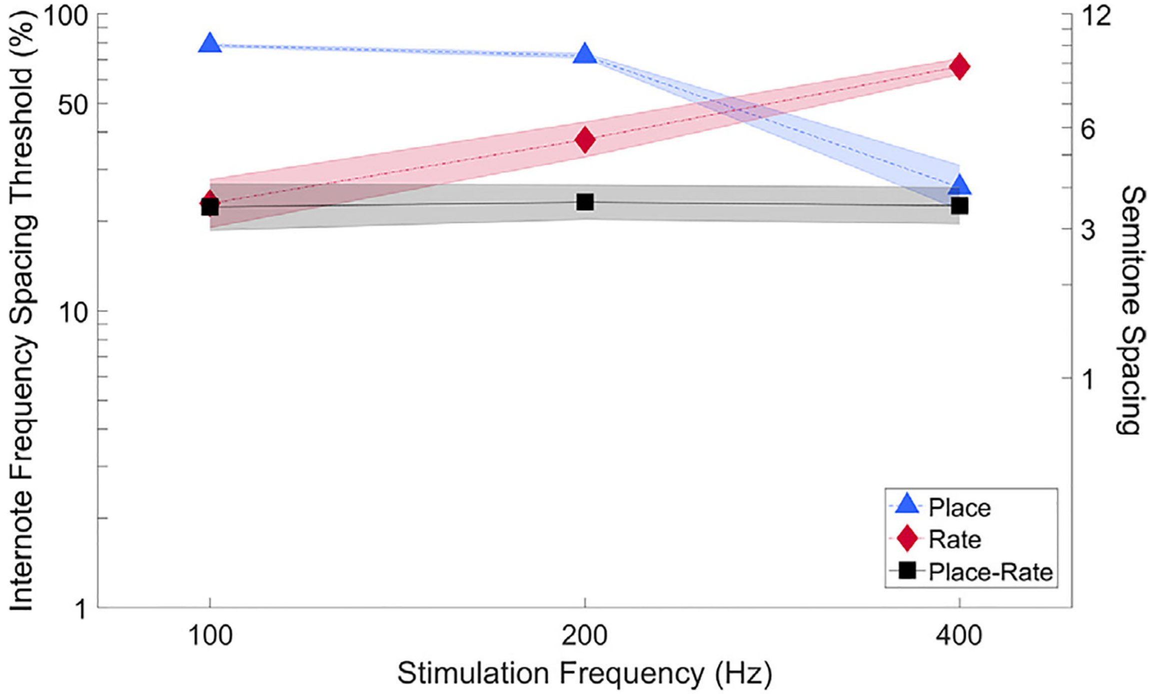

Fig. 2.

Internote frequency spacing thresholds for melodic contour identification as a function of center-note frequency. Symbols indicate thresholds averaged across subjects with shaded error bars showing standard errors of the means.

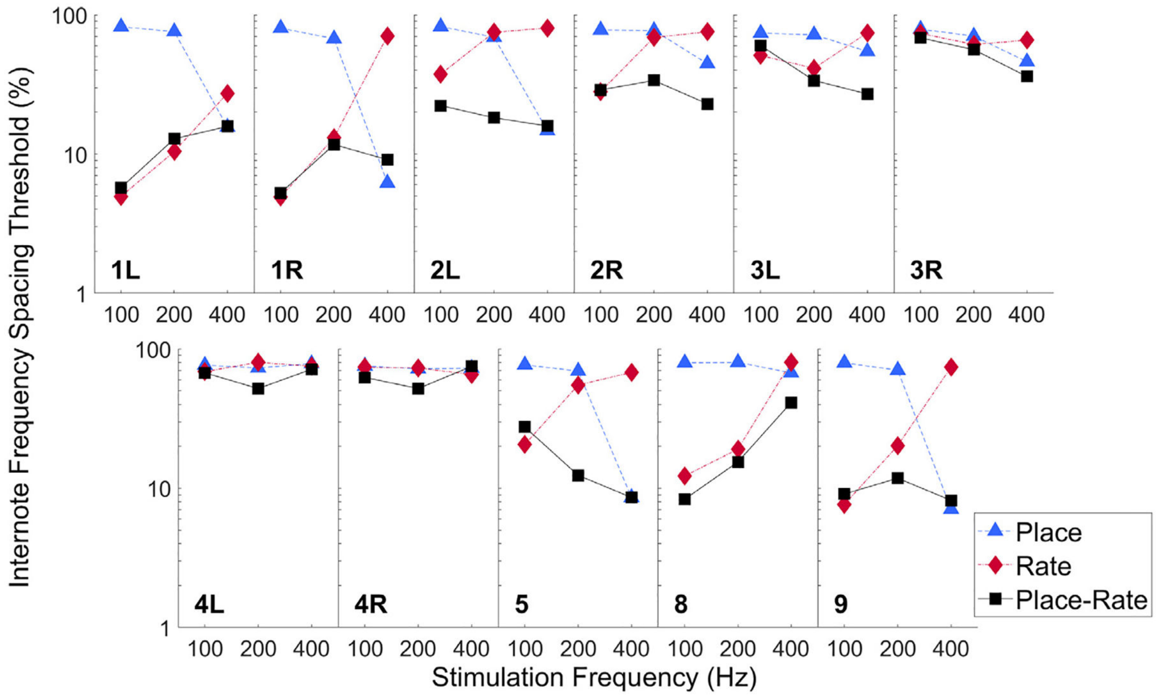

Fig. 3.

Individual internote frequency spacing thresholds for melodic contour as a function of center-note frequency. Symbols indicate internote frequency spacing thresholds averaged across repetitions.

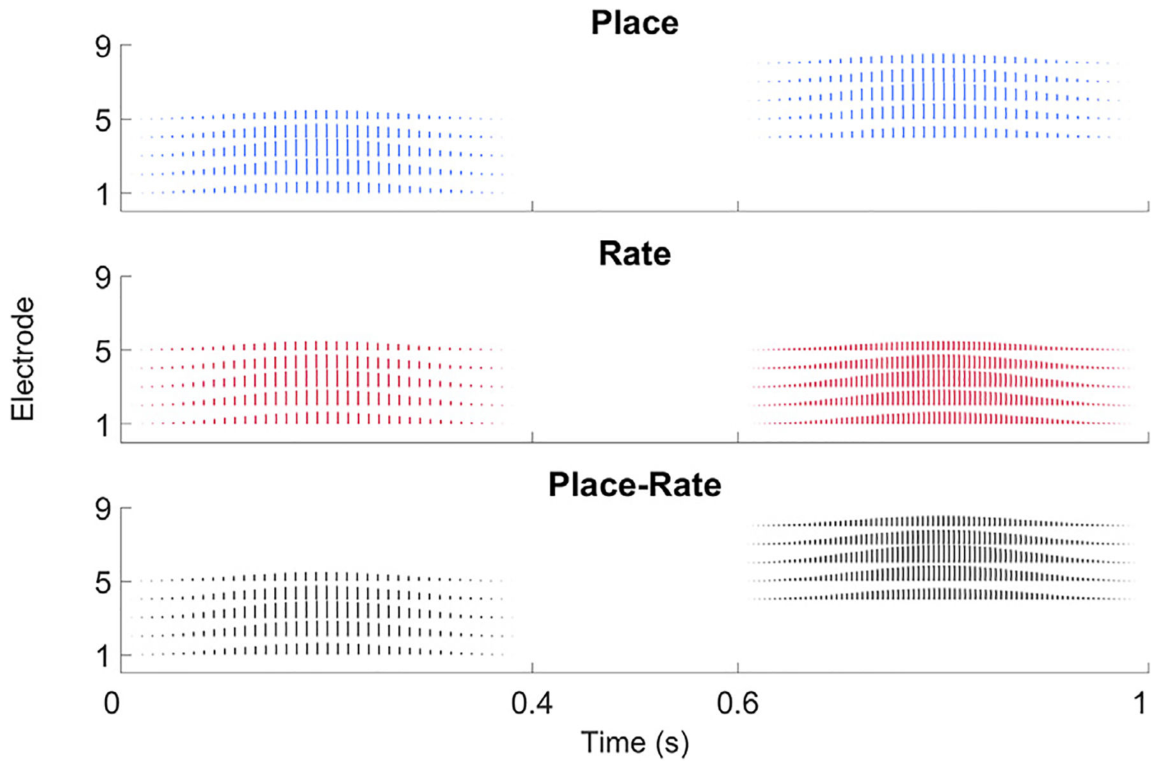

Fig. 4.

Example stimuli for experimental conditions of place, rate, and combined place-rate. The first panel shows the condition where place of stimulation is varied from 100 to 200 Hz and rate is held constant at the base frequency of 100 Hz for both the standard and target stimuli. The second panel shows the condition where rate of stimulation is varied from 100 to 200 Hz and place of stimulation is held constant at the base frequency of 100 Hz for both the standard and target stimuli. The third panel shows the combined place-rate condition with both place and rate covaried from 100 Hz for the standard stimulus to 200 Hz for the target stimuli.

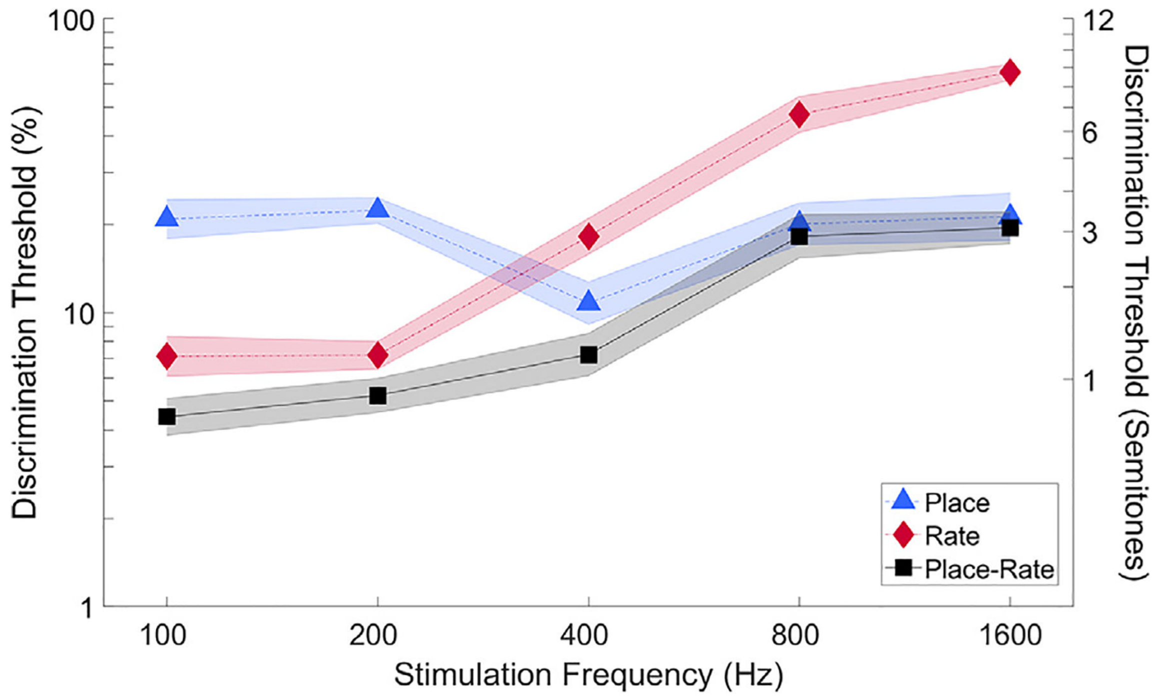

Fig. 5.

Frequency discrimination with multi-electrode stimuli averaged across participants for the factors of stimulation cue and frequency with shaded error bars showing standard errors of the means.

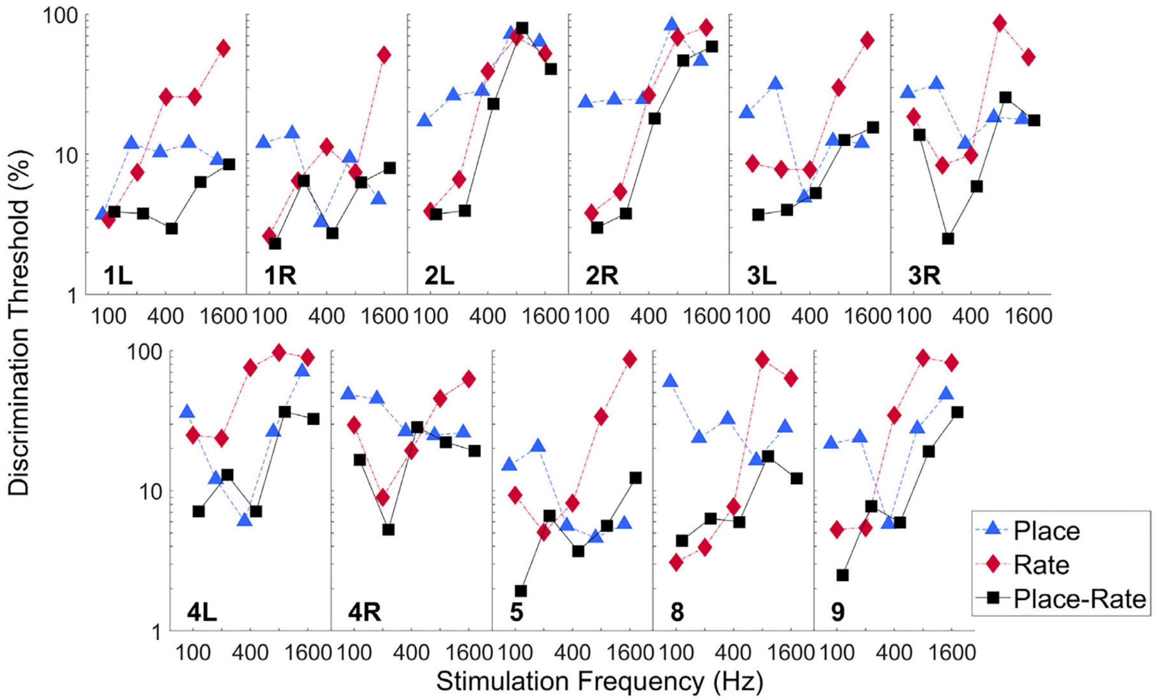

Fig. 6.

Individual frequency discrimination as a function of frequency. Symbols show discrimination thresholds averaged across repetitions for each cue type.

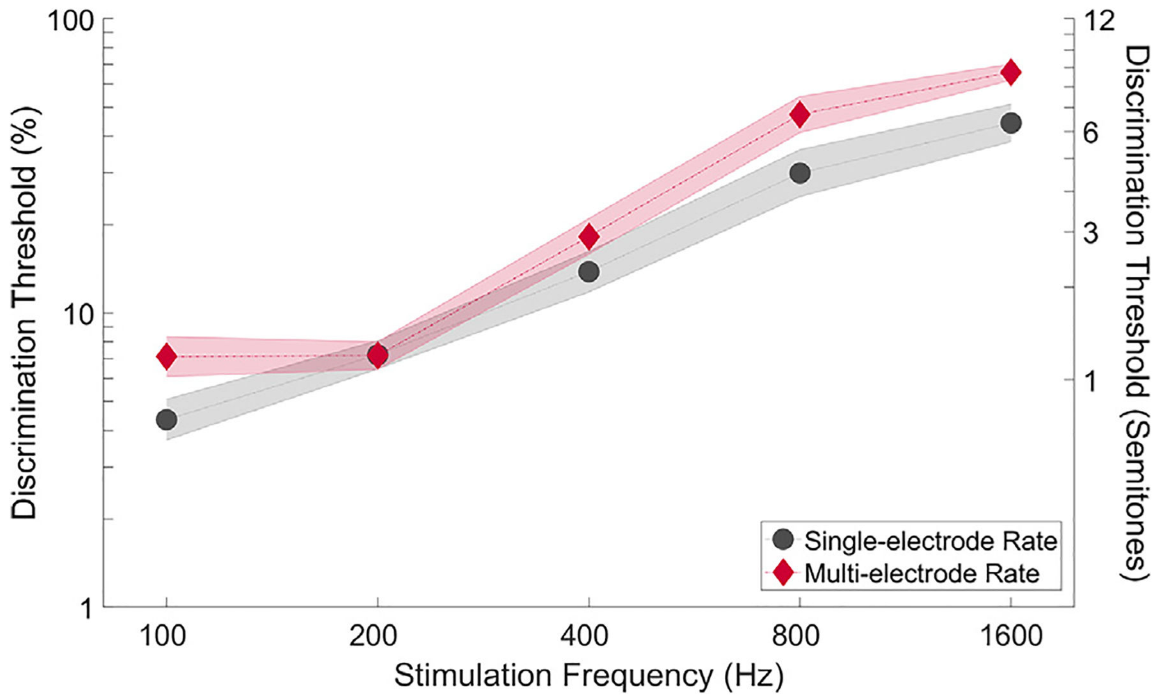

Fig. 7.

Single and multi-electrode rate discrimination as a function of frequency. Symbols indicate discrimination thresholds averaged across subjects with shaded error bars indicating standard errors of the means.

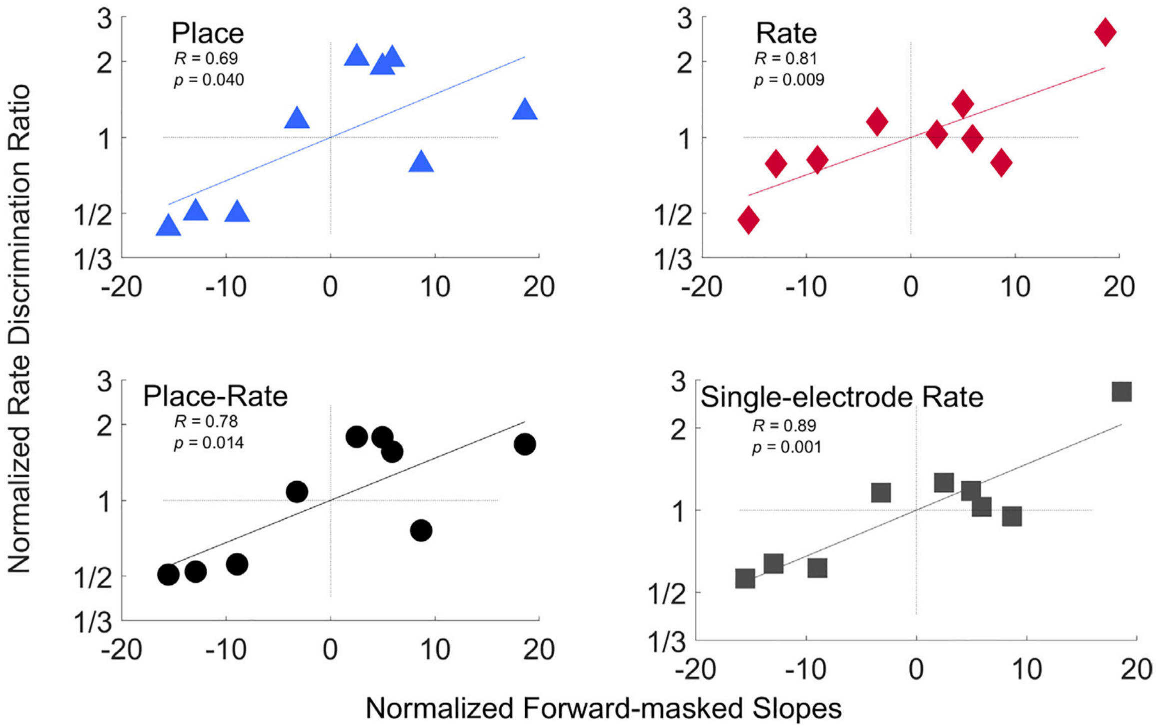

Fig. 8.

Correlations between forward-masked threshold slopes normalized by the subtraction of the average with frequency discrimination thresholds for subjects 1 through 5 for the stimulation cues of place, rate, place-rate, and single-electrode rate.

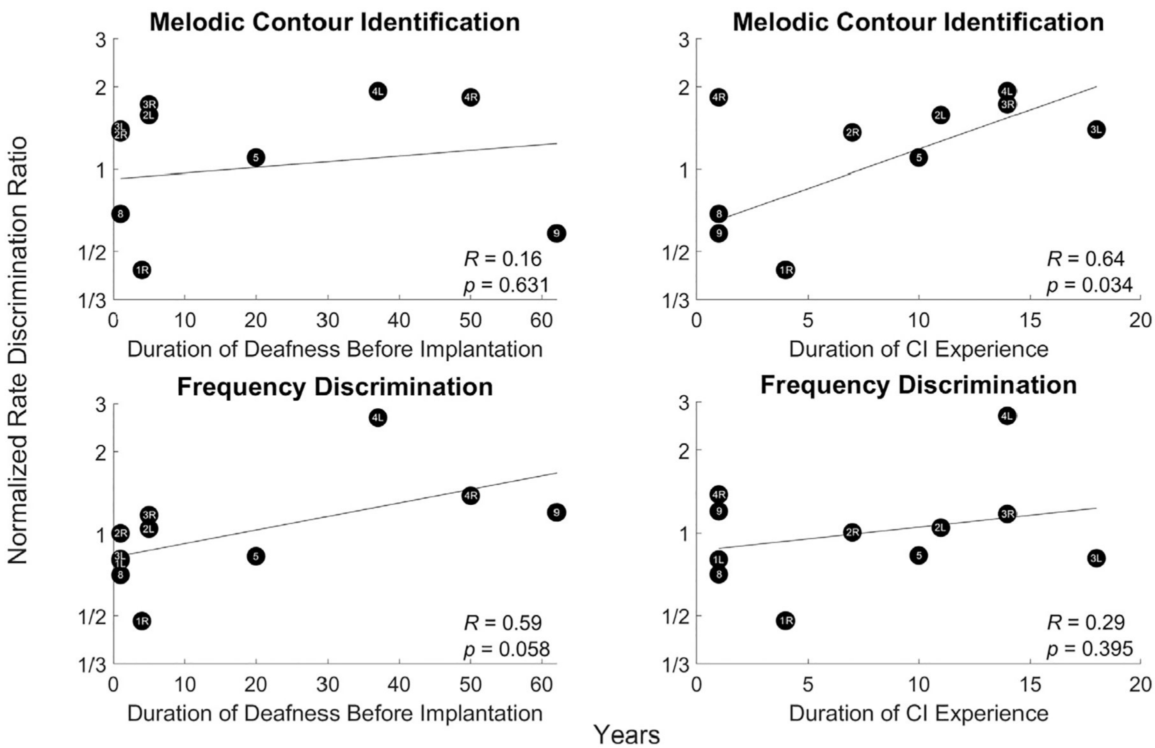

Fig. 9.

Correlations between rate discrimination, as measured by melodic contour and simple frequency discrimination, and the metrics of duration of deafness before implantation and cochlear implant experience.

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Table 1

Subject information. Age at time of testing and age at onset of hearing loss is given in years. Duration of profound hearing loss prior to implantation is given in years and estimated from subject interviews. SNHL = sensorineural hearing loss.

ID	Age	Gender	Ear Tested	Etiology	Age at Onset	Years Implanted	Implant model	Processor	Duration of Deafness	Age at Implantation
C1	47	M	Both	Meniere's	39	L:1 R:4	L:CI532 R:CI24RE (CA)	L:N7 R:N7	L:1 R:4	L:46 R:43
C2	34	F	Both	Unknown	15	L:11 R:7	L:CI24RE (CA) R:CI24RE (CA)	L:N7 R:N7	L:5 R:1	L:27 R:23
C3	72	F	Both	Progressive SNHL	40	L:18 R:14	L:CI24R (CS) R:CI24RE (CA)	L:N6 R:N6	L:1 R:5	L:54 R: 58
C4	58	M	Both	Progressive SNHL	Birth	L:14 R:1	L:CI24RE (CA) R:CI532	L:N7 R:N7	L:37 R:50	L:44 R:57
C5	80	M	Right	Noise Induced	40	10	CI24RE (CA)	N6	20	70
C8	70	F	Right	Sudden SNHL	68	1	CI522	N7	1	68
C9	72	M	Right	Unknown	L:40 R:Birth	1	CI532	N7	L:7 R:60	71