Place-Pitch Interval Perception With a Cochlear Implant

Natalia Stupak, Ann E. Todd, and David M. Landsberger

Objectives: Pitch is poorly perceived by cochlear implant (CI) users. However, as it is not well understood how pitch is encoded with electric stimulation, improving pitch representation with a CI is challenging. Changes in place of stimulation along the cochlea have been described as changes in pitch and can be accurately ranked by CI users. However, it remains unknown if place-pitch can be used to encode musical intervals, which are a necessary attribute of pitch. The objective of these experiments is to determine if place-pitch coding can be used to represent musical intervals with a CI.

Design: In the first experiment, 10 CI users and 10 normal hearing (NH) controls were tested on their sensitivity to changes in the semitone spacing between each of the notes in the melody "Happy Birthday." The changes were implemented by uniformly expanding or compressing the frequency differences between each note in the melody. The participant's task was to scale how "out-of-tune" the melody was for various semitone spacing distortions. The notes were represented by pure-tones ≥440 Hz to minimize potential useful temporal information from the stimuli. A second experiment replicated the first experiment using single-sided deafened CI users allowing for a within-subject control. A third experiment verified that the CI users who participated in Experiment 1 were each able to determine pitch direction reliably.

Results: Unlike NH listeners, CI listeners often ranked all distortions of interval spacing similarly in both the first and second experiment, and no effect of interval spacing was detected across CI users. Some participants found distorted interval spacings to be less out-of-tune than the nominally correct interval spacings. However, these patterns were inconsistent across listeners. Although performance was better for the NH listeners, the third experiment demonstrated that the CI listeners were able to reliably identify changes in pitch direction from place-pitch coding.

Conclusions: The data suggest that place-pitch intervals are not properly represented through a CI sound processor. Some limited support is found for place-pitch being useful for interval encoding as some participants demonstrated improved ratings for certain interval distortions. Presumably the interval representation for these participants could be improved by a change to the frequencies represented by each electrode. However, as these patterns vary across listeners, there is not a universal correction to frequency representation that will solve this issue. As results are similar for single-sided deafened CI users, the limitations in ratings are likely not limited by an eroded representation of the melody caused by an extended duration of deafness.

Key words: Cochlear implant, Musical intervals, Pitch, Place-pitch.

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INTRODUCTION

Although modern cochlear implants (CIs) provide most users with sufficient speech understanding to carry on conversations and even talk on the telephone, music perception suffers (e.g., Kong et al. 2004; Gfeller et al. 2005). Presumably, one reason music perception is difficult is that pitch information is not well conveyed to an implant user through a clinical sound processor (Green et al. 2004; Gfeller et al. 2007; Sucher & McDermott 2007). However, as it is not well understood how pitch is encoded with electric stimulation, improving pitch representation with a CI is challenging.

Pitch direction changes are generally encoded with a CI correctly, provided the difference between the notes is sufficiently large (e.g., Galvin et al. 2007; Sucher & McDermott 2007). That is, listeners can correctly rank or identify the order of pitches. We describe being able to identify the correct order of pitches as having "ordinal" pitch. However, ordinal pitch is not sufficient for musical perception. Higher frequencies must not only be perceived as being higher in pitch, but also appropriate musical intervals must be maintained. That is, when increasing from 440 Hz to 660 or 880 Hz, the pitch shift must not only be perceived as higher, but also as a proper musical interval of a fifth or an octave. If the correct musical relationships are not maintained, then harmonic structures will be perceived as inharmonic, chords will sound discordant, and melodies will be out-of-tune. We refer to a change in frequency producing the appropriate change in perceived pitch as "interval" pitch. Using clinical fittings, CI users perceive melodies as more out-of-tune than normal hearing (NH) controls (Luo et al. 2014). This may explain the relatively poor listening enjoyment to music relative to that of a NH ear (Landsberger et al. 2020).

Pitch can theoretically be encoded by the temporal properties of a signal as well as by the place within the cochlea providing the signal. In acoustic hearing, the temporal and place cues are inherently connected with many stimuli, but with electrical hearing, they are provided independently. Temporal information can be provided by the rate of stimulation on a single electrode while place information can be encoded by the location of the electrode contact providing the stimulation. With electrical hearing, changes in rate on a single electrode up to approximately 300 Hz and changes in electrode providing stimulation have both been described as changes in pitch (e.g., Eddington et al. 1978; Tong et al. 1983; Townshend et al. 1987; McKay et al. 1994; Galvin & Fu 2005). Despite both being described as pitch, the perceptual qualities associated with rate and place coding are independent (e.g., Tong et al. 1983; McKay et al. 2000; Landsberger et al. 2018). Nevertheless, when combined, rate and place cues interact on the overall perceived pitch (e.g., Stohl et al. 2008; Luo et al. 2012; Landsberger et al. 2016).

Intervals could potentially be encoded by place coding, but it would require finer resolution than 12 to 22 places of stimulation provided by the number of electrodes on the array. Fortunately, more places of stimulation can be provided than the number of electrodes using "virtual channels." Virtual channels can be created via simultaneous (e.g., Donaldson et al. 2005; Firszt et al. 2007) or sequential (McDermott & McKay 1994; Galvin et al. 2009; Landsberger & Galvin 2011) stimulation of two or more electrodes. All commercial CI signal processing strategies (e.g., ACE, FS4, Fidelity 120, Optima) provide sequential virtual channels while a subset also provide

Department of Otolaryngology, New York University School of Medicine, New York, USA

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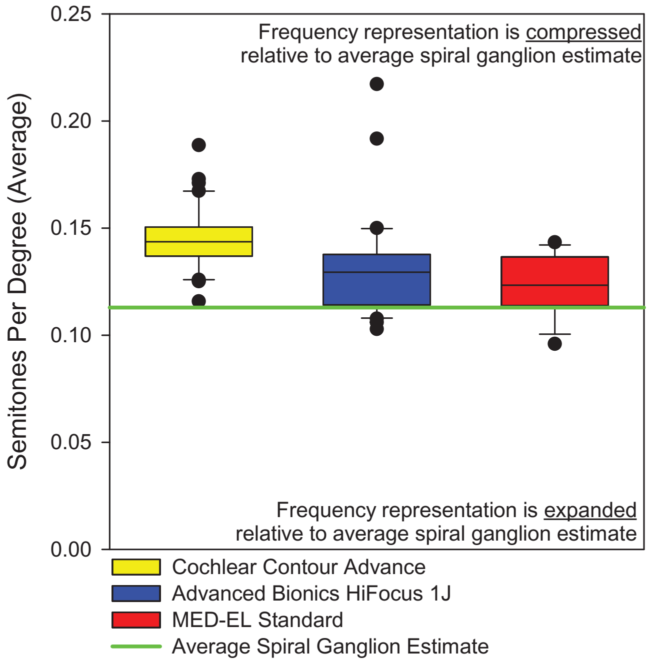

Fig. 1. Average number of semitones per degree as represented by three different electrode arrays as extracted from Landsberger et al. (2015). The corresponding average semitones per degree represented along the spiral ganglion with acoustic hearing is represented by the green line based on data extracted from Stakhovskaya et al. (2007).

simultaneous virtual channels (e.g., Fidelity 120 and Optima). Taking advantage of sequential virtual channels, Swanson et al. (2009) investigated music ability using place-pitch by presenting melodies via pure-tones to a CI processor. Because of the broad filters in a CI processor, the pure-tones were represented on multiple electrodes, creating sequential virtual channels to represent place-pitch. Because the pure-tones were a single frequency at a fixed amplitude, the Cochlear sound processor represented the pure-tones at a fixed-rate without modulations. The resulting output is a representation of the pure-tone stimuli represented almost exclusively by place-pitch information as is well illustrated in Figure 2 of Swanson et al. (2009). Using pure-tones presented to the processor, listeners were able to identify the correctly played version of "Old MacDonald" from a version where one of the notes was shifted by five semitones, suggesting that place-pitch alone may be useful to encode pitch. This finding is remarkable in that it has been postulated that electrical place-pitch represents brightness and not pitch (e.g., McDermott 2004; Moore and Carlyon 2005). However, Lamping et al. (2017) asked listeners to scale the pitch and brightness of various rate/place combinations and found that place-pitch was not better described by the term "brightness" than the term "pitch." Furthermore, Vermeire et al. (2013) used multidimensional scaling to demonstrate that a change in electric place of stimulation from a CI can be described by the same perceptual dimension as a change in pure-tone frequency provided to an acoustic hearing ear. Therefore, further investigation of using place-pitch to encode interval pitch is warranted.

Even if place of stimulation can represent interval pitch, the place-pitch representation from a CI is likely to be distorted relative to that provided in a normal ear. That is, for a given location in the cochlea, the frequency provided by the CI is likely to be lower than the frequency represented at that location by acoustic stimulation (see Landsberger et al. 2015 for an overview). This is not necessarily a problem for interval pitch in that if all frequencies are represented with a fixed semitone shift, the result should be a musical transposition with intervals preserved. Along the spiral ganglion of a NH ear, the frequency range of 250 to 8000 Hz is represented by approximately 0.113 semitones per degree as calculated from the data provided by Stakhovskaya et al. (2007). Data extracted from Landsberger et al. (2015) suggest that when a similar frequency range is represented by a CI, the semitones per degree are higher on average (0.145, 0.132, and 0.124 semitones per degree for Cochlear Contour Advance, Advanced Bionics HiFocus 1J, and MED-EL Standard arrays). However, variability in these relationships can be found for users of all three systems (Fig. 1). Data points above the green line in Figure 1 suggest that, relative to acoustic stimulation of the cochlea, the CI presents frequency in a reduced space along the cochlea. The few data points below the green line represent CIs that provide frequency in an expanded space along the cochlea relative to acoustic stimulation. As such, even if place-pitch is able to support interval pitch, interval pitch may still be distorted because of where along the spiral ganglion the CI represents frequencies.

The full story is likely even more complicated. One limitation is that the calculation of semitones per degree provides only a rough estimation of the place/frequency relationship, because the relationship is not perfectly linear (e.g., Stakhovskaya et al. 2007; Landsberger et al. 2015). As a result, the degree per semitone calculation may describe an overall compression or expansion of the place-frequency relationship, ignoring local frequency misalignments that are likely to occur. Another limitation is that this analysis ignores the plasticity of the auditory system. It has been well documented that the perceived pitch associated with a given electrode often shifts over time (e.g., Svirsky et al. 2004; Reiss et al. 2007, 2014). Typically, shortly after implantation, the pitch of a given electrode is represented approximately by the frequency that would be provided at the location of the electrode with acoustic hearing, but over time shifts toward the frequency represented by that electrode in the user's clinical map. On one hand, this adaptation would likely correct for small deviations in place-pitch interval relationships. On the other hand, this adaptation is likely to be variable (and at best only semipredictable) across participants and even electrodes, making the place-pitch relationships even more difficult to predict.

In the present study, we examined if stimuli providing primarily place-pitch and limited temporal information can be used to provide interval-pitch information to CI users. In the first two experiments, CI users, normal acoustic-hearing listeners, and single-sided deafened (SSD) CI users (i.e., with one NH and one implanted ear) were evaluated to determine if the tuning of a familiar melody ("Happy Birthday") was sensitive to global changes in semitone spacings using a protocol similar to that of Todd et al. (2017). In the third experiment, the CI users from the first experiment were tested on a pitch contour task (Galvin et al. 2007) to verify that each of the CI users was able to correctly identify pitch direction using place cues. All electric stimuli were presented by playing pure-tones to the CI users' clinical processors to produce primarily place-pitch cues as described by Swanson et al. (2009).

EXPERIMENT 1: INTERVAL PLACE-PITCH MEASURED BY MELODY TUNING

In Experiment 1, listeners were asked to rate how out-of-tune a familiar melody ("Happy Birthday") was perceived. The melody was presented using place information using acoustic pure-tones at either the correct tuning, or with the frequency spacing between semitones stretched or compressed. It was expected that if place-pitch provides interval pitch, varying the semitone compression/expansion would affect the ratings of how out-of-tune the song was. The protocol used was based on a protocol originally used in Todd et al. (2017). The experiment differed in the frequency range of stimuli.

METHODS

Participants

Ten postlingually deafened adult CI users were tested using their clinical processors and standard settings. Participants represented all FDA approved manufacturers in the United States (four Advanced Bionics users, three Cochlear users, and three MED-EL users). Additionally, 10 NH participants (as defined by passing a 25 dB HL screening at 250, 500, 1,000, 2,000, and 4,000 Hz) participated in this experiment as a control group. NH participants were between 21 and 47 years of age with a median age of 28 years. All participants provided informed consent in accordance with the IRB regulations for the New York University School of Medicine. Specific demographics for the CI users are presented in the top portion of Table 1.

Stimuli

Stimuli consisted of the song "Happy Birthday" played using pure-tones concatenated to form a 25-note sequence. These acoustic pure-tones were created using a 16-bit depth resolution and a 44.1 kHz sampling frequency. All pure-tones had the same root-mean-square (rms) amplitude. Ten-ms Hann on- and off-ramps were used for each pure-tone. The root note (lowest note) for each of the stimuli was either 440 Hz (A4) or 880 Hz (A5). These frequencies were selected to be more than half an octave above the commonly observed 300 Hz upper limit of good temporal pitch perception with electric hearing (e.g., Eddington et al. 1978; Simmons et al. 1981; Shannon 1983; Tong et al. 1983; Blamey et al. 1984; Zeng 2002; Landsberger & McKay 2005; Kreft et al. 2010). Each sequence of tones corresponding to the rhythm of "Happy Birthday" had pure-tone durations equal to 500 ms × the relative durations where the relative durations = (0.75, 0.25, 1, 1, 1, 2, 0.75, 0.25, 1, 1, 1, 2, 0.75, 0.25, 1, 1, 1, 1, 1, 0.75, 0.25, 1, 1, 1, 2). The frequency (f) of the tones within each sequence was equal to $f = \text{root note} \times (2^{(1/12)})^{(\text{semitone exponent} \times \text{steps})}$. Steps were equal to (0, 0, 2, 0, 5, 4, 0, 0, 2, 0, 7, 5, 0, 0, 12, 9, 5, 4, 2, 10, 10, 9, 5, 7, 5), which corresponded to the number of semitones between the lowest note (root note) and other notes in the song, "Happy Birthday." The spacing between notes could be physically correct, where the semitone changes between notes were as defined by the song (i.e., semitone exponent = 1). Alternatively, the spacing between notes could all be compressed (semitone exponent < 1) or expanded (semitone exponent > 1). The semitone exponents used to form various levels of in- or out-of-tune stimuli were equal to 0.43, 0.63, 0.83, 1, 1.23, 1.43, or 1.63.

Procedure

All stimuli were presented over a speaker at 0-degree azimuth, 1 m from the listener, in a double-walled soundproof booth. CI users with residual hearing had their ears plugged for this experiment. Unilateral implant users were tested using their implant while bilateral implant users were tested using their two implants together.

The participants were instructed to listen to each stimulus sequence (i.e., "Happy Birthday") and rate each sequence on how out-of-tune it was perceived using a visual scale ranging from 0 to 100 on a desktop computer. Scaling was performed by adjusting a scroll bar using a computer mouse. The scroll bar had markers labeled with descriptors to aid in the rating process. The following descriptors were used: "in tune," "a little out of tune," "out of tune," and "unrecognizable," with "in tune" equaling a value of 100, and "unrecognizable" equaling a value of 0. After rating the sequence, the participant saved the response and the scale reset before presentation of the next sequence. The participant was able to replay each sequence as many times as desired before finalizing their rating. There were a total of 70 stimulus sequences consisting of 5 blocks of 14 (7 semitone exponents × 2 root notes) trials randomly presented to the participant. Note that the software to run the experiment was custom-written in MATLAB for Todd et al. (2017).

RESULTS

Results for the NH group are presented in Figure 2. Average out-of-tune ratings for each root note are plotted in a different color and symbol as a function of the semitone exponent.

Each panel represents individual participant data. Plots are consistent with expectations in that the physically correct sequence (semitone exponent 1.0) was rated as least out-of-tune for both root notes for 9 of the 10 NH participants. As the tuning distortions increased (i.e., the semitone exponent deviated from 1.0), the out-of-tune ratings increased, creating a visual "V" shape in data points.

Results for the CI users are plotted in Figure 3. Contrary to the NH data, a semitone exponent of 1.0 does not provide a consistent local minimum across participants. This suggests that, unlike the NH listeners, the CI population does not interpret the physically correct tuning as being less out-of-tune than other sequences where the tuning is physically distorted. Although there is great variability across listeners and root notes, ratings as a function of semitone exponent are typically constant (i.e., no distinct "V-Shape"), suggesting that overall, CI users do not find that changing the semitone spacing of the sequence has an effect of degree to which the sequence is out-of-tune. Although there were no clear consistent patterns across participants, some participants (such as C101 or M107) exhibited local minimums, suggesting that they may have some sensitivity to the semitone exponent.

The across-participant NH and CI average data are presented in the left and right panels of Figure 4. Two-way repeated-measures analysis of variances (ANOVAs; factors: semitone exponent and root note) were calculated separately for NH and CI listeners. A main effect of semitone exponent was detected for NH listeners ($F(6,54) = 32.289$, $p < 0.001$), but not for CI listeners ($F(6,54) = 1.359$, $p = 0.248$). The main effect of root note was not significant for either group (NH: $F(1,9) = 2.018$,

TABLE 1. Subject Demographics for CI Users

Code	Gender	Age at Testing	Manufacturer	Age at Implantation	Implant and Electrode	Strategy	Stimulation Rate (pps)	Etiology	Onset	Musical Experience
C101	M	70	Advanced Bionics	RE: 66	RE: HR90K HiFocus 1J	RE: HiRes Optima-P	RE: 3712	Unknown	Progressive	No musical experience
C107	F	44	Advanced Bionics	RE: 31	RE: CII HiFocus 1J	RE: HiRes Optima-P	RE: 2750	Unknown	Progressive	Little to no experience
C110	M	32	Advanced Bionics	RE: 28 LE: 22	RE: HR90K HiFocus 1J LE: HR90K HiFocus 1J	RE: HiRes Optima-P LE: HiRes Optima-P	LE: 1954 RE: 2855	Unknown	Congenital	Unknown
C114	F	70	Advanced Bionics	RE: 67	RE: HR90K HiFocus MS	RE: HiRes Optima-S	RE: 1515	Meniere's/ Autoimmune	Progressive	Played piano as a youth/ does not listen to music now
M104	F	55	MED-EL	RE: 52 LE: 50	RE: Concert Flex 24 LE: Concert Medium	RE: FSP LE: FSP	RE: 1117 LE: 1709	Unknown	Congenital	Little to no experience
M107	M	60	MED-EL	LE: 56	LE: Concert Flex 28	LE: FS4	LE: 1442	Unknown	Congenital	Has musical experience—likes music, sounds how he remembers it
M110	F	63	MED-EL	RE: 61 LE: 65	RE: Unknown LE: Unknown	RE: Unknown LE: Unknown	RE: Unknown LE: Unknown	Unknown	Progressive	Sang preimplantation
N102	F	63	Cochlear Ltd.	RE: 60	RE: CI24RE(CA)	RE: ACE	RE: 900	Unknown	Progressive	Sang preimplantation
N103	F	59	Cochlear Ltd.	RE: 51	RE: CI24RE(CA)	RE: ACE	RE: 900	Genetic/ paternal family history	Progressive	Played piano, though never liked music. Implant made music worse
N104	F	65	Cochlear Ltd.	LE: 56	LE: CI24RE(CA)	LE: ACE	LE: 900	Spinal meningitis	Progressive	Played clarinet as child
Code	**Gender**	**Age at Testing**	**Manufacturer**	**Age at Implantation**	**Implant and Electrode**	**Strategy**	**Stimulation Rate (pps)**	**Etiology**	**Onset**	
SSD-C1	F	33	Advanced Bionics	RE: 30	RE: HR90K HiFocus MS	RE: HiRes Optima-P	RE: 2652	Unknown	Sudden	
SSD-N1	M	68	Cochlear Ltd.	RE: 62	RE: CI512	RE: ACE	RE: 900	Unknown	Sudden	
SSD-N6	M	47	Cochlear Ltd.	RE: 45	RE: CI512	RE: ACE	RE: 900	Unknown	Sudden	
SSD-N7	M	55	Cochlear Ltd.	RE: 54	RE: CI512	RE: ACE	RE: 900	Unknown	Sudden	
SSD-N9	M	27	Cochlear Ltd.	LE: 26	LE: CI512	LE: ACE	LE: 900	Temporal Bone Fracture	Sudden	

CI = cochlear implant; LE, left ear; pps, pulses per second; RE, right ear; SSD, single-sided deafened.

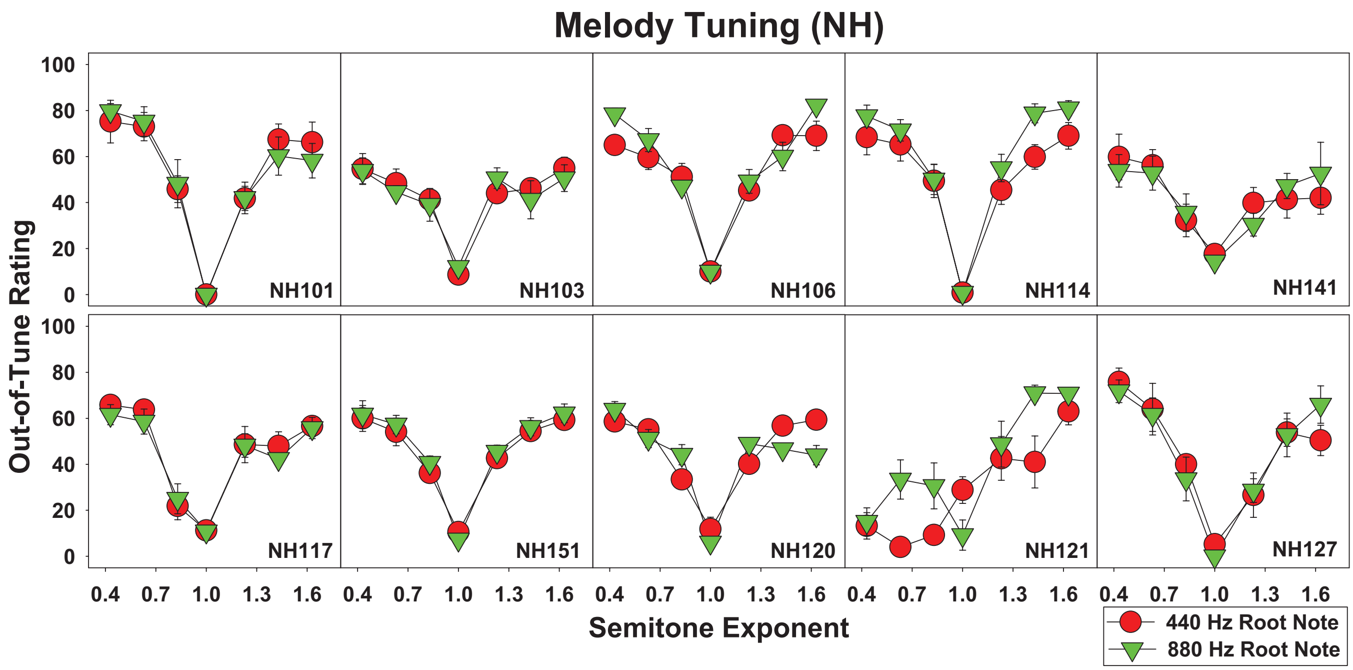

Fig. 2. Out-of-tune ratings as a function of semitone exponent for 10 normal-hearing listeners. Circles indicate ratings of melodies with a 440 Hz root note while triangles indicate ratings of melodies with an 880 Hz root note. Error bars indicate ±1 standard error of the mean.

$p = 0.189$; CI: $F(1,9) = 2.108$, $p = 0.180$), nor were the interactions (NH: $F(6,54) = 0.802$, $p = 0.573$; CI: $F(6,54) = 0.459$, $p = 0.835$).

EXPERIMENT 2: INTERVAL PLACE-PITCH MEASURED BY MELODY TUNING WITH SSD CI USERS

The data in Experiment 1 failed to detect a consistent effect of semitone spacing on the perceived tuning of the melody "Happy Birthday" for CI users using primarily place-pitch coding. These limitations may be caused by limitations of place-pitch with a CI. However, an additional limitation with the data collected with CI users in Experiment 1 is that it relied on their ability to remember the tuning of "Happy Birthday" accurately. This may not be a fair assumption for CI users who no longer have access to acoustic hearing. To address this concern, out-of-tune trainings were measured in SSD CI users. These participants have one NH ear and a contralateral

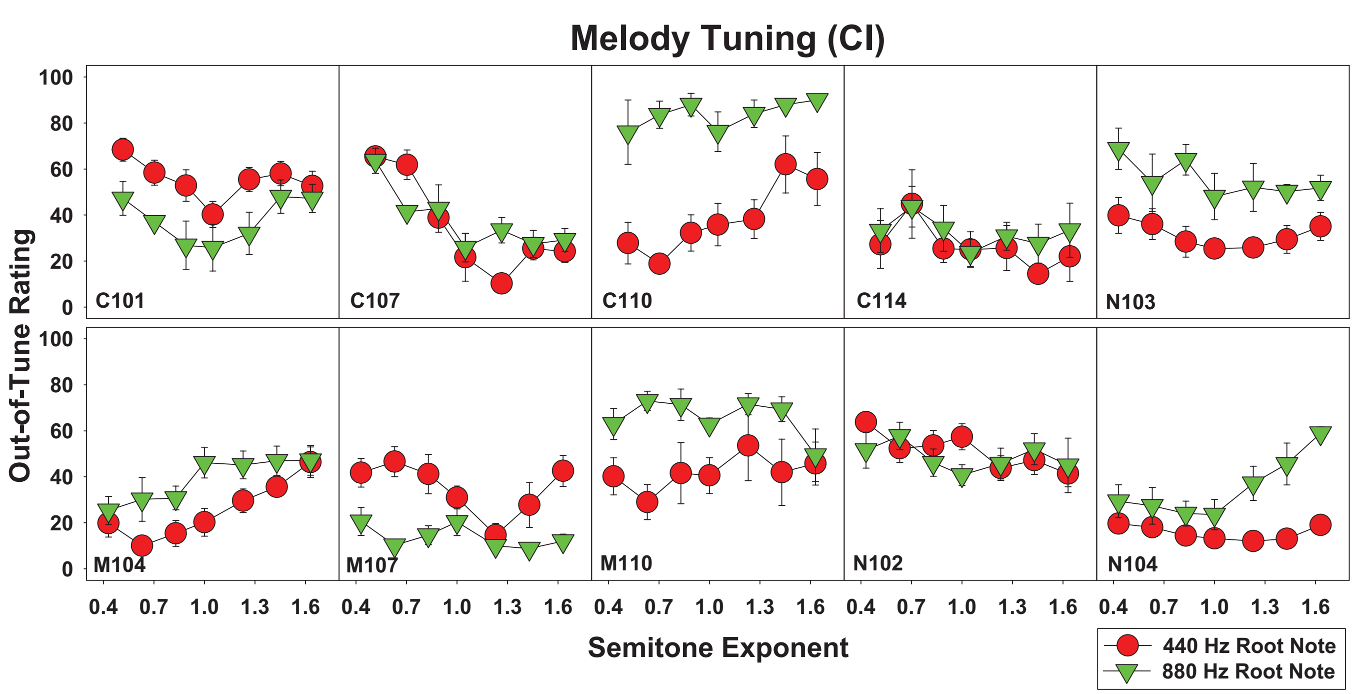

Fig. 3. Out-of-tune ratings as a function of semitone exponent for 10 CI users. Circles indicate ratings of melodies with a 440 Hz root note while triangles indicate ratings of melodies with an 880 Hz root note. Error bars indicate ±1 standard error of the mean. CI, cochlear implant.

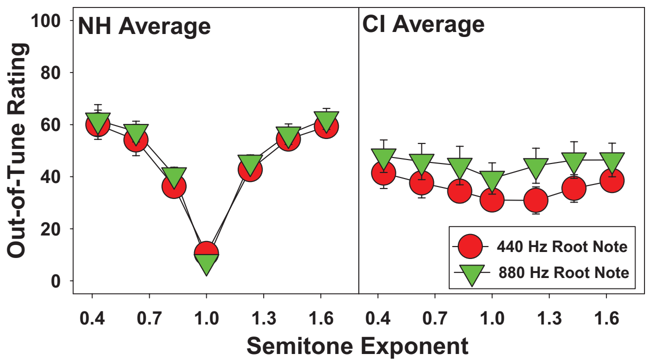

Fig. 4. Average out-of-tune ratings as a function of semitone exponent for 10 CI users (right panel) and 10 NH participants (left panel). Circles indicate ratings of melodies with a 440 Hz root note while triangles indicate ratings of melodies with an 880 Hz root note. Error bars indicate ±1 standard error of the mean. CI, cochlear implant; NH, normal hearing.

deafened ear with a CI. As these listeners presently have access to a normal ear, it can be assumed that they have maintained a proper representation of the melody "Happy Birthday." By testing their out-of-tune scaling with their NH ear alone, it can be verified that the listener produces "V-Shaped" data similar to that produced by the NH listeners in Experiment 1. If so, data collected with the CI alone in these SSD–CI users can be interpreted with the assumption that they have an adequate mental representation of the melody and understanding of the task.

METHODS

Participants

In this experiment, 5 SSD adults with a CI (four Cochlear users and one Advanced Bionics user) participated. All participants provided informed consent in accordance with the IRB regulations for the New York University School of Medicine. Specific demographic data are presented in the bottom portion of Table 1.

Stimuli and Procedure

The stimuli and procedure for Experiment 2 were nearly identical to those used in Experiment 1. Participants were tested first with their NH ear alone, and second with their CI alone, and third with both ears together. Testing was done with the NH ear first such that the participant would be familiarized and practiced with the procedure before exposure to the stimuli through the implant. Stimuli were not presented via free-field. The stimuli for the NH ear were presented via headphones (Sony MDR-7506) driven by an Edirol UA-25 soundcard. The stimuli for the CI ear were presented directly from the Edirol UA-25 soundcard to the CI sound processor via a direct audio input cable. Stimulus levels were set by playing a short musical segment alternating between the ears and asking the listeners to adjust the volume for NH and CI ears independently until they were equally loud at a most-comfortable level using a protocol described in Landsberger et al. (2020).

RESULTS

The out-of-tune ratings for the SSD participants are presented in Figure 5. Each row represents an individual participant's data. Each column represents a listening condition: NH ear alone data are presented in the left panel, CI ear alone data are presented in the middle panel, and data for both ears together are presented in the right panel. The NH ear alone data (left column) are similar to that for the NH group in Experiment 1 (Fig. 2) in that the data are organized into a "V-Shape" with a minimum out-of-tune rating with a semitone exponent of 1.0. The CI only data (middle column) are similar to that of the CI group from Experiment 1 (Fig. 3) in that most of the participants rated the out-of-tune attribute of the melody similarly across semitone exponents. Nevertheless, there are notable exceptions. For example, with the 880 Hz root note, SSD-N6 provides a "V-Shaped" pattern with a minimum at the 0.83 semitone exponent. This suggests that for this participant/stimulus combination, tuning of the melody can improved by reducing the spacing between notes relative to the physically correct stimulus.

Data were analyzed for each listening condition (NH, CI, and NH + CI ears) using a two-way-repeated measures ANOVA with factors of semitone spacing and root note. Results for the NH ear alone were consistent with results for the NH listeners in Experiment 1 in that a main effect of semitone was detected ($F(6,24) = 62.983$, $p < 0.001$), while the main effect of root note ($F(1,4) = 1.218$, $p = 0.332$) and the interaction ($F(6,24) = 0.552$, $p = 0.764$) were not. Results for the CI ear alone were consistent with results for the CI listeners in Experiment 1 in that no significant main effects of semitone spacing ($F(6,24) = 1.350$, $p = 0.274$), root note ($F(1,4) = 0.117$, $p = 0.749$), or their interaction ($F(6,24) = 0.461$, $p = 0.830$) were detected. Results with both the CI and NH ears together were consistent with the NH ear alone in that a main effect of semitone was detected ($F(6,24) = 55.104$, $p < 0.001$), while the main effect of root note ($F(1,4) = 5.388$, $p = 0.081$) and the interaction ($F(6,24) = 1.971$, $p = 0.110$) were not.

EXPERIMENT 3: ORDINAL PITCH AS MEASURED BY MELODIC CONTOURS

Given the relatively poor performance of the CI users determining tuning of the "Happy Birthday" melody using place-coding, it was important to verify that the CI listeners were able to determine pitch direction using only place-pitch cues. To do so, melodic contours were measured with a CI ear using the melodic contour intervals test developed by Galvin et al. (2007).

METHODS

Participants

The same 10 CI users and 9 of the 10 NH adults tested in Experiment 1 also participated in Experiment 3.

Stimuli

Stimuli consisted of sequences of five notes, each consisting of a single pure-tone, played in succession. Each tone was 250 ms long with 10 ms onset and offset ramps. The interval between notes was 50 ms. The five-note sequences were organized into one of nine contours: rising, falling, flat, rising-falling, rising-flat, falling-rising, falling-flat, flat-rising, and flat-falling. The specific configurations for these contours are illustrated in

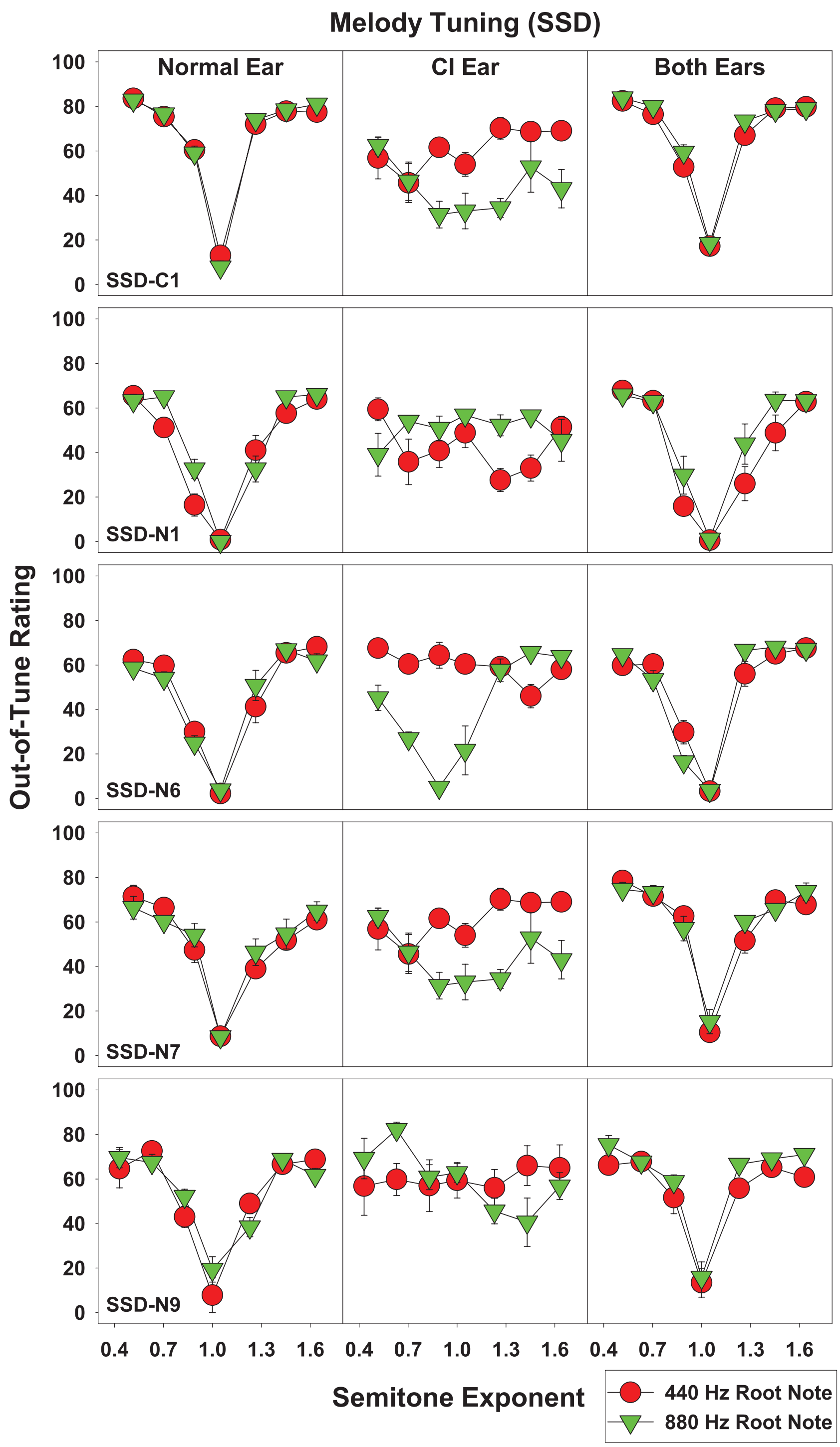

Fig. 5. Out-of-tune ratings as a function of semitone exponent for 5 SSD participants. Each row of panels represent data from a single participant. From left to right, the three columns represent ratings for the normal-hearing ear, the implanted ear, and the two together. Circles represent ratings of the melodies with a 440 Hz while triangles represent melodies with an 880 Hz root note. Error bars indicate ±1 standard error of the mean. NH, normal hearing; SSD, single-sided deafened.

Figure 6. The spacing between notes in the contours was either 1, 2, 3, 4, or 5 semitones. Within a given stimulus, the semitone spacing between notes was constant. The root notes for each of the stimuli were either 440 Hz (A4) or 880 Hz (A5). A total of 90 contours were used (9 contours × 5 semitone spacings × 2 root notes). Note that the stimuli used in this experiment differed from the Galvin et al. (2007) in that pure-tones were used in the present experiment instead of harmonic complexes. Pure-tone stimuli are important for the experiment as they are represented using primarily place cues as described by Swanson et al. (2009).

Procedure

In a given trial, a participant listened to one of the 90 stimuli. They were instructed to select which of the nine contour shapes

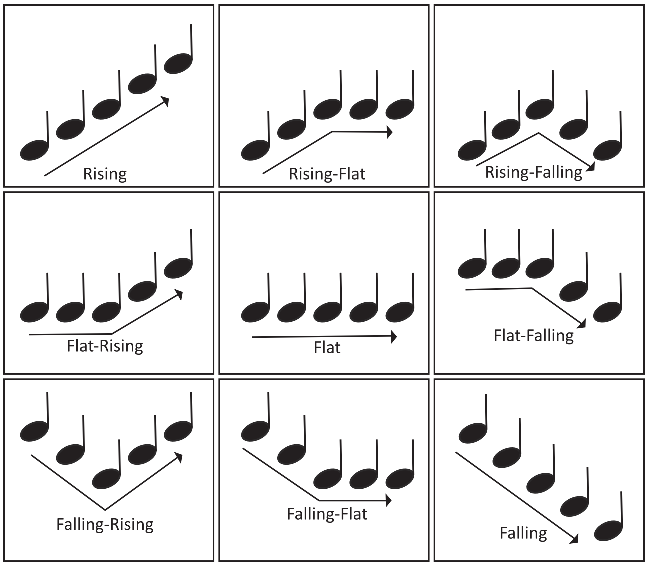

Fig. 6. Melodic contour identification stimuli description.

they had just heard by clicking on a graphic representation of the corresponding contour using a mouse (see Fig. 6). In a given block of trials, each of the stimuli were played once in a random order. Each participant completed three blocks of trials.

Stimuli were presented over a loudspeaker at 60 dBA. Participants sat facing the speaker approximately 1 meter away in a double-walled soundproof booth. The experiment was controlled using i-Cast software (available for free download from http://icast.emilyfufoundation.org). The original sound files (with F0 and first two harmonics) provided by the software and used in Galvin et al. (2007) were replaced by sound files containing the previously described stimuli using only pure-tones. CI users with residual hearing had their ears plugged for this experiment. Unilateral implant users were tested using their implant while bilateral implant users were tested using their two implants together.

RESULTS

The percent correct for both root notes were averaged together for each CI participant and plotted in Figure 7 as a function of semitone spacing. Data from individual participants are presented in panels with a white background. The average across CI participants is presented along with the average across NH participants in the panel with a gray background. With the exception of M110's 1-semitone spacing data, all CI and NH responses were above chance (11.1%) for all semitone spacings. One-sample post hoc *t* tests for each semitone spacing were significantly different than chance, even after Type I error correction (Rom 1990). Even the condition providing the worst performance (1-semitone spacing for CI users) was significantly different from chance ($t(9) = 6.477$, $p < 0.001$); the calculated *t* statistics for the other semitone spacings were even higher. Overall, the data suggest that the participants were able to perform the task with above chance performance, although their performance decreased as the semitone distance decreased.

To compare the performance differences between the NH and CI groups, a mixed-effect ANOVA was calculated using number of semitones as a within-subject factor and listener group (CI or NH) as a between-subject factor. Significant differences between subject groups ($F(1,17) = 18.214$, $p = 0.001$), semitone spacings ($F(4,68) = 25.766$, $p < 0.001$), and the interaction ($F(4,68) = 16.295$, $p<0.001$) were detected.

DISCUSSION

The present study suggests that across participants, place-pitch provided through a CI speech processor does not provide correct interval pitch. As the CI listeners were able to reliably rank the pitch direction using the contour task but were insensitive to the note spacing that depends on musical pitch, the data is consistent with the idea that place-pitch percept is actually a brightness or other timbre cue (e.g., Plomp 1976; Schubert and Wolfe 2006) and not a pitch cue. However, there are multiple other explanations for the data other than place-pitch is brightness and cannot provide musical pitch.

One potential explanation is that place-pitch is distorted differently for each listener. If so, then analyses (such as the ANOVA used in the present study) that look for similar patterns across participants may fail to detect an effect of place-pitch across participants when the pattern of place-pitch varies across participants. Variability across participants may be caused by variations in the place-frequency representation along the cochlea (e.g., Landsberger et al. 2015; Canfarotta et al. in press), quality of the electrode-neural interface (e.g., Bierer 2007; Zhou & Pfingst 2016), and state of adaptation to the place-pitch (e.g., Svirsky et al. 2001; Reiss et al. 2014; Vermeire et al. 2015). Indeed, a close inspection of the data suggest that individuals may be differently sensitive to place-pitch tuning. For example, the data for C101 has clearly defined minimums when the semitone exponent is 1, suggesting that he perceives interval pitch from place-only cues, as he considered expansion and compression of the melody to be less in tune. With the 440 Hz root-note melody, C110 and M104 both report that the melody sounds relatively in-tune when the semitone spacing is compressed with a semitone exponent of 0.63, and expanding the spacing with higher exponents makes the melody be perceived as more out-of-tune. These results are consistent with the reduced degree-per-semitone representation of Figure 1 combined with incomplete place-pitch adaptation. Other participants, such as C107 and M107, have patterns suggesting that a melody is most in-tune when the spacing between notes is represented by pure-tones spaced further than would be represented by an acoustic hearing ear. Another pattern represented by other participants (such as C114 and N102) shows little effect on perceived tuning even with large changes in semitone spacing.

However, even if the data from some individual participants suggest sensitivity to distortions in interval pitch, the scaled differences between the most and least in-tune ratings from an implanted ear are generally much smaller than with a normal acoustic ear. This suggests that even if the CI listener is sensitive to interval pitch with place cues, listeners were more sensitive to interval pitch with their normal ear. One potential explanation for this finding is that place-pitch representation provided through a CI may be overly broad for precise interval-pitch encoding. The monopolar stimulation used clinically provides an inherently broad pattern of stimulation (e.g., Bierer and Middlebrooks 2002; Landsberger et al. 2012). The overall stimulation pattern will be even broader when multiple electrodes provide monopolar stimulation to produce sequential virtual channels, as described by Landsberger and Galvin (2011) and

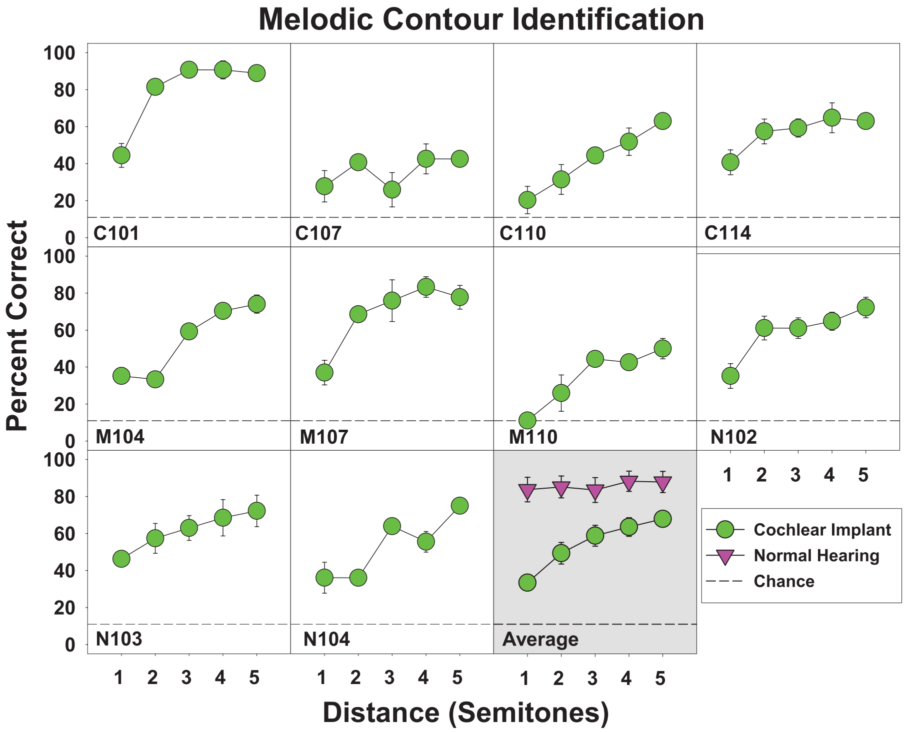

Fig. 7. Performance (in percent correct) on the melodic contour task as a function of the semitone differences between adjacent notes. Each panel with a white background represents performance for an individual CI user. The panel with the gray background represents the average performance across all 10 CI users as well as average performance across 9 NH participants. Error bars indicate ±1 standard error of the mean. The dashed line indicates chance performance (11.1%). CI, cochlear implant; NH, normal hearing.

illustrated in Figure 8. Perhaps place-pitch would provide better interval pitch if it were encoded by a narrower spread of excitation using a single Monopolar Virtual Channel (e.g., Donaldson et al. 2005; Firszt et al. 2007) or a current focused virtual channel (e.g., Landsberger & Srinivasan 2009; Padilla et al. 2017). A potential limitation in the experiment is the assumption that distortions in place-pitch with a CI are consistent across the frequencies represented by the electrode array. If the magnitudes of the distortions are variable within a listener across the frequencies and cochlear locations represented by the CI array, it may be that the tuning of some of the intervals in the melody will be better than other intervals, and therefore no one semitone spacing will provide ideal tuning, potentially resulting in the shallow out-of-tune curves produced by most CI listeners.

It is important to note the temporal cues that are provided by each of the sound coding strategies used in the present experiment. Cochlear's ACE signal processing (Vandali et al. 2000) provides no temporal cues to the input frequency. Similarly, the 1 "fine-structure channel" in M104's FSP map provides no temporal cues for the input frequencies of 440 Hz and above. MED-EL's FS4 and FS4p strategies provide some temporal information for the stimuli between approximately 440 and 880 Hz while the Advanced Bionics Fidelity 120 and Optima strategies provide temporal information for all pure-tones used in this experiment. Sample outputs from each of the manufacturers are presented in Figure 8 and detailed explanations of how the strategies process pure-tones are provided in a supplemental Appendix http://links.lww.com/EANDH/A704.

While temporal information was encoded by the Advanced Bionics devices and the FS4/FS4p strategies for the 440 Hz root-note stimuli, it is unlikely that it provided much useful pitch information to the listeners in this experiment. The lowest frequency was 440 Hz, which was chosen to ensure that every note in the experiment was more than half an octave above the commonly observed 300 Hz upper limit of good temporal pitch perception with electric hearing (e.g., Eddington et al. 1978; Simmons et al. 1981; Shannon 1983; Tong et al. 1983; Blamey et al. 1984; Zeng 2002; Landsberger & McKay 2005; Kreft et al. 2010) as well as the phase-locking rate limit found in the inferior colliculus to stimulation from a cochlear implant (Middlebrooks & Snyder 2010). Although a very small number of CI users have been reported with higher upper temporal limits (e.g., Hochmair-Desoyer et al. 1983; Wilson et al. 1997; Kong & Carlyon 2010), the resolution for rate discrimination for frequencies above 300 Hz tends to be quite poor. For example, Landsberger & McKay (2005) found that CI users were able to discriminate between 400-Hz and 800-Hz unmodulated single-electrode pulse trains above chance level (25% correct) less than 30% of the time. If it is difficult to discriminate an octave change in frequency, it is likely much more difficult to discriminate 1 to 2 semitones for base frequencies above 440 Hz using only temporal cues. Furthermore, Landsberger & McKay (2005) found that CI participants had great difficulty in ranking the pitch of discriminable high-rate pulse trains, and Kong & Carlyon (2010) found frequent pitch reversals at similar high rates. This suggests that listeners may have discriminated between pulse trains using some cue other than pitch. In summary, while we cannot unequivocally rule out the possibility that temporal rate cues did not contribute to the present pattern of results for the Advanced Bionics and MED-EL CI users, it seems unlikely.

One limitation in many CI pitch and melody experiments is that if a CI user has difficulty performing a task, it is unknown

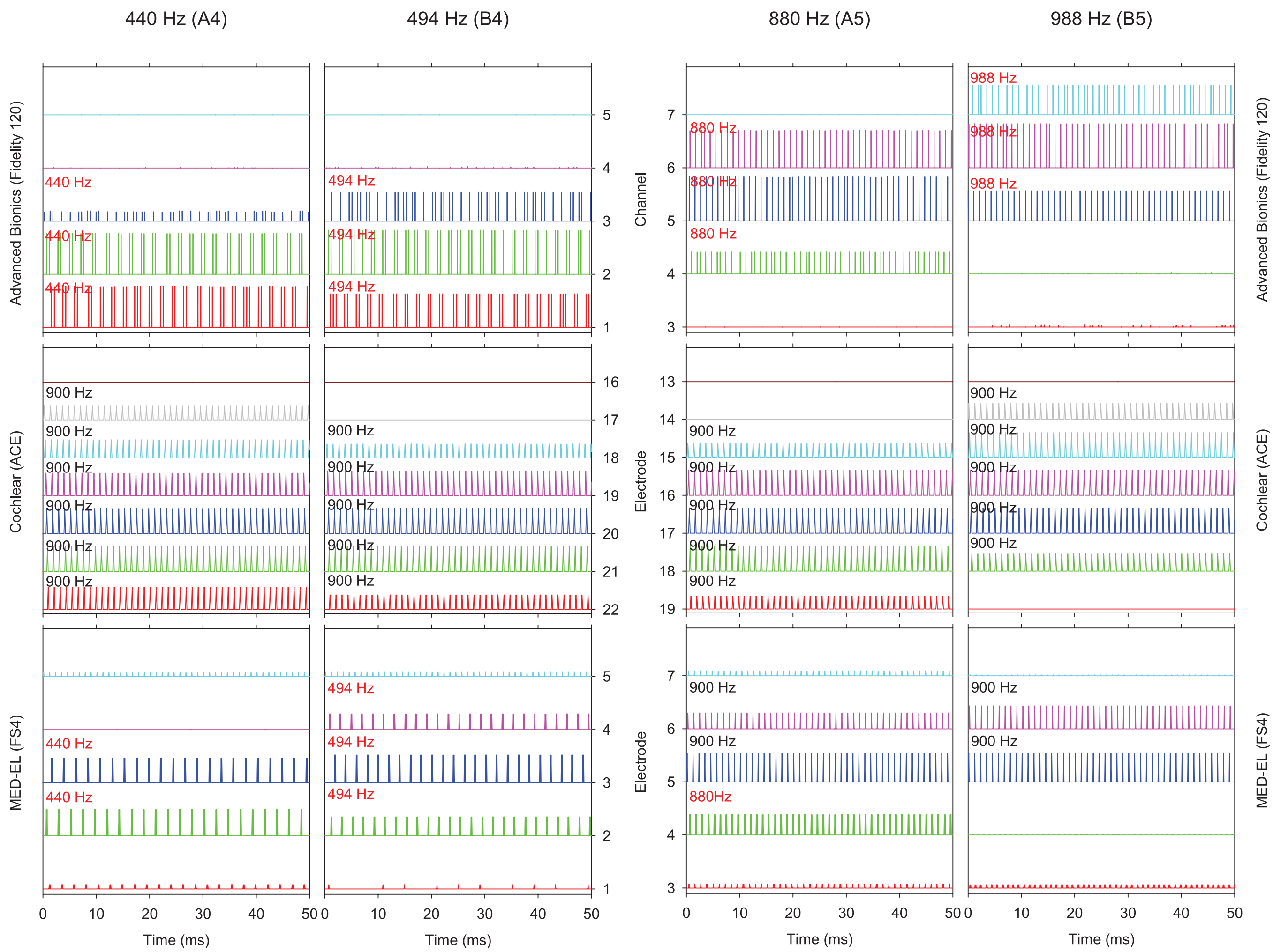

Fig. 8. Electrodograms illustrating the outputs of sound coding strategies from Advanced Bionics (top row), Cochlear (middle row), and MED-EL (bottom row). The four columns represent four different input pure-frequencies (440, 494, 880, and 988 Hz) corresponding to the two root notes used in the experiments and a note two-semitones above. Within each plot, outputs of each electrode (or virtual channel) are plotted to represent both the timing and amplitude of each pulse. The plots are scaled to illustrate the temporal properties of the stimuli. The stimulation frequency for each electrode/channel is provided in red when the frequency corresponds to the input frequency and in black when it corresponds to a fixed rate defined by the fitting strategy. Electrodograms were generated with Batch-C2-Simulator (Advanced Bionics), Nucleus Matlab Toolbox (Cochlear), or simCoding (MED-EL).

if the limitation is the representation of the stimulus through the CI, an over-reliance on memory of pitch and music, or a participant's lack of understanding of the task. The data collected in Experiment 1 suffer from this limitation, as do many other experiments involving musical tasks such as familiar melody (e.g., Gfeller et al. 2000 2002 2003; Looi et al. 2004, 2008; Olszewski et al. 2005) interval adjustment (e.g., Pijl & Schwartz 1995a, 1995b), or melody distortion tasks (e.g., Swanson et al. 2009, 2019; Marimuthu et al. 2016). This issue is potentially magnified as it may be common to hear "Happy Birthday" sung out of tune by nonprofessional singers, and it is plausible that the CI user has an accurate memory of an incorrectly sung version of the song. In Experiment 2, the issue of musical memory, mental representation of the song, and participant's ability to understand the task were addressed by replicating Experiment 1 in SSD users with a CI such that each participant could serve as their own control. Given that NH ears of the SSD listeners provided similar data to the NH participants in Experiment 1 and the implanted ears of the SSD listeners provided similar data to the CI participants, it can be presumed that the differences observed between NH and CI data were not related to comprehension of the task or memory and familiarity of the melody.

While the results suggest that place-pitch through a clinical processor does not provide consistent interval pitch, the conclusions about the contributions of place-pitch to musical pitch or timbre are less clear. The lack of a strong effect of interval tuning with place-pitch is compatible with the hypothesis that pitch corresponds to temporal coding and brightness corresponds to place-pitch. Nevertheless, the relationship between place-pitch and brightness is not clear cut. Lamping et al. (2017) specifically measured brightness and pitch as a function of rate and place changes with a CI. They found that while both changes in rate and place could be described by changes in both pitch and brightness, neither rate nor place was better described by a rate or brightness change. This suggests that rate and place cannot be explained simply as a change in pitch or brightness. Similarly, using a modified melodies task, it has been suggested that rate and place cues independently can provide interval-pitch information for many participants, although performance with these tasks is well below that of NH listeners (Swanson et al. 2009, 2019; Marimuthu et al. 2016).

When a similar interval tuning experiment was conducting using only rate cues on a single electrode (Todd et al. 2017), the results were similarly unconvincing. As such, if the data from the current experiment is used as evidence that place-pitch does not encode pitch, then the data from Todd et al. (2017) must also be used as evidence that rate-pitch does not encode pitch either. One potential explanation is that the poor pitch conveyed by rate or place is caused by a detrimental property of electric stimulation. Another possible explanation is that pitch is dependent on a combination of rate and place cues, and as such is poorly represented when only one is manipulated. There are multiple data sets that are compatible with this explanation. For example, it has been demonstrated that although rate and place are perceptually independent (e.g., Tong et al. 1983; Landsberger et al. 2018), combining these cues in a complementary or contradictory manor modifies the pitch percept in ways consistent with both cues combining to contribute to pitch (e.g., Stohl et al. 2008, Luo et al. 2012; Landsberger et al. 2016). Furthermore, pitch matching electric to acoustic stimuli is easier (i.e., variability is reduced) when the rate and place information is combined (e.g., Rader et al. 2016), suggesting pitch percepts depend on both rate and place information.

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The authors have no conflicts of interest to declare.

Address for correspondence: Natalia Stupak, Department of Otolaryngology, New York University School of Medicine, 550 1st Avenue, STE NBV 5E5, New York, NY 10016, USA. E-mail: natalia.stupak@nyumc.org

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REFERENCES

Bierer, J. A. (2007). Threshold and channel interaction in cochlear implant users: Evaluation of the tripolar electrode configuration. *J Acoust Soc Am, 121*, 1642–1653.

Bierer, J. A., & Middlebrooks, J. C. (2002). Auditory cortical images of cochlear-implant stimuli: Dependence on electrode configuration. *J Neurophysiol, 87*, 478–492.

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

Canfarotta, M. W., Dillon, M. T., Buss, E., Pillsbury, H. C., Brown, K. D., & O'Connell, B. P. (2020). Frequency-to-place mismatch: Characterizing variability and the influence on speech perception outcomes in cochlear implant recipients. *Ear and hearing*. Advance online publication. https://doi.org/10.1097/AUD.0000000000000864.

Donaldson, G. S., Kreft, H. A., Litvak, L. (2005). Place-pitch discrimination of single- versus dual-electrode stimuli by cochlear implant users (L). *J Acoust Soc Am, 118*, 623–626.

Eddington, D. K., Dobelle, W. H., Brackmann, D. E., et al. (1978). Auditory prostheses research with multiple channel intracochlear stimulation in man. *Ann Otol Rhinol Laryngol, 87*(6 Pt 2), 1–39.

Firszt, J. B., Koch, D. B., Downing, M., Litvak, L. (2007). Current steering creates additional pitch percepts in adult cochlear implant recipients. *Otol Neurotol, 28*, 629–636.

Galvin, J. J. 3rd, & Fu, Q. J. (2005). Effects of stimulation rate, mode and level on modulation detection by cochlear implant users. *J Assoc Res Otolaryngol, 6*, 269–279.

Galvin, J. J. 3rd, Fu, Q. J., Nogaki, G. (2007). Melodic contour identification by cochlear implant listeners. *Ear Hear, 28*, 302–319.

Galvin, J. J., Fu, Q.-J., Oba, S. I. (2009). *Virtual Channels with Sequential Stimulation in Cochlear Implant Users*. In ARO Midwinter Meeting, Baltimore, MD.

Gfeller, K., Christ, A., Knutson, J., et al. (2003). The effects of familiarity and complexity on appraisal of complex songs by cochlear implant recipients and normal hearing adults. *J Music Ther, 40*, 78–112.

Gfeller, K., Olszewski, C., Rychener, M., et al. (2005). Recognition of "real-world" musical excerpts by cochlear implant recipients and normal-hearing adults. *Ear Hear, 26*, 237–250.

Gfeller, K., Turner, C., Mehr, M., et al. (2002). Recognition of familiar melodies by adult cochlear implant recipients and normal-hearing adults. *Cochlear Implants Int, 3*, 29–53.

Gfeller, K., Turner, C., Oleson, J., et al. (2007). Accuracy of cochlear implant recipients on pitch perception, melody recognition, and speech reception in noise. *Ear Hear, 28*, 412–423.

Gfeller, K., Witt, S., Stordahl, J., et al. (2000). The effects of training on melody recognition and appraisal by adult cochlear implant recipients. *J Acad Rehabil Audio*, *33*, 115–138.

Green, T., Faulkner, A., Rosen, S. (2004). Enhancing temporal cues to voice pitch in continuous interleaved sampling cochlear implants. *J Acoust Soc Am, 116*(4 Pt 1), 2298–2310.

Hochmair, I., Nopp, P., Jolly, C., et al. (2006). MED-EL cochlear implants: State of the art and a glimpse into the future. *Trends Amplif*, *10*, 201–219.

Hochmair-Desoyer, I. J., Hochmair, E. S., Burian, K., et al. (1983). Percepts from the Vienna cochlear prosthesis. *Ann N Y Acad Sci, 405*, 295–306.

Kong, Y. Y., & Carlyon, R. P. (2010). Temporal pitch perception at high rates in cochlear implants. *J Acoust Soc Am, 127*, 3114–3123.

Kong, Y. Y., Cruz, R., Jones, J. A., et al. (2004). Music perception with temporal cues in acoustic and electric hearing. *Ear Hear, 25*, 173–185.

Kreft, H. A., Oxenham, A. J., Nelson, D. A. (2010). Modulation rate discrimination using half-wave rectified and sinusoidally amplitude modulated stimuli in cochlear-implant users. *J Acoust Soc Am, 127*, 656–659.

Lamping, W., Santurette, S., Marozeau, J. (2017). Verbal attribute magnitude estimates of pulse trains across electrode places and stimulation rates in cochlear implant listeners. In S. Santurette, T. Dau, J. C.-Dalsgaard, et al. (Eds.), *Proceedings of the International Symposium on Auditory and Audiological Research* (pp. 215–222). The Danavox Jubilee Foundation.

Landsberger, D., & Galvin, J. J. 3rd. (2011). Discrimination between sequential and simultaneous virtual channels with electrical hearing. *J Acoust Soc Am, 130*, 1559–1566.

Landsberger, D. M., Marozeau, J., Mertens, G., et al. (2018). The relationship between time and place coding with cochlear implants with long electrode arrays. *J Acoust Soc Am, 144*, EL509.

Landsberger, D. M., & McKay, C. M. (2005). Perceptual differences between low and high rates of stimulation on single electrodes for cochlear implantees. *J Acoust Soc Am, 117*, 319–327.

Landsberger, D. M., Padilla, M., Srinivasan, A. G. (2012). Reducing current spread using current focusing in cochlear implant users. *Hear Res, 284*, 16–24.

Landsberger, D. M., & Srinivasan, A. G. (2009). Virtual channel discrimination is improved by current focusing in cochlear implant recipients. *Hear Res, 254*, 34–41.

Landsberger, D. M., Svrakic, M., Roland, J. T., Jr., et al. (2015). The relationship between insertion angles, default frequency allocations, and spiral ganglion place pitch in cochlear implants. *Ear Hear, 36*, e207–e213.

Landsberger, D. M., Vermeire, K., Claes, A., et al. (2016). Qualities of single electrode stimulation as a function of rate and place of stimulation with a cochlear implant. *Ear Hear, 37*, e149–e159.

Landsberger, D. M., Vermeire, K., Stupak, N., et al. (2020). Music is more enjoyable with two ears, even if one of them receives a degraded signal provided by a cochlear implant. *Ear Hear, 41*, 476–490.

Looi, V., McDermott, H., McKay, C., et al. (2004). Pitch discrimination and melody recognition by cochlear implant users. *Int Congr Ser*, *1273*, 197–200.

Looi, V., McDermott, H., McKay, C., Hickson, L. (2008). Music perception of cochlear implant users compared with that of hearing aid users. *Ear Hear, 29*, 421–434.

Luo, X., Masterson, M. E., Wu, C. C. (2014). Melodic interval perception by normal-hearing listeners and cochlear implant users. *J Acoust Soc Am, 136*, 1831–1844.

Luo, X., Padilla, M., Landsberger, D. M. (2012). Pitch contour identification with combined place and temporal cues using cochlear implants. *J Acoust Soc Am, 131*, 1325–1336.

Marimuthu, V., Swanson, B. A., Mannell, R. (2016). Cochlear implant rate pitch and melody perception as a function of place and number of electrodes. *Trends Hear*, *20*.

McDermott, H. J. (2004). Music perception with cochlear implants: A review. *Trends Amplif, 8*, 49–82.

McDermott, H. J., & McKay, C. M. (1994). Pitch ranking with nonsimultaneous dual-electrode electrical stimulation of the cochlea. *J Acoust Soc Am, 96*, 155–162.

McKay, C. M., McDermott, H. J., Carlyon, R. P. (2000). Place and temporal cues in pitch perception: Are they truly independent? *Acoust Res Lett Online*, *1*, 25–30.

McKay, C. M., McDermott, H. J., Clark, G. M. (1994). Pitch percepts associated with amplitude-modulated current pulse trains in cochlear implantees. *J Acoust Soc Am, 96*(5 Pt 1), 2664–2673.

Middlebrooks, J. C., & Snyder, R. L. (2010). Selective electrical stimulation of the auditory nerve activates a pathway specialized for high temporal acuity. *J Neurosci, 30*, 1937–1946.

Moore, B. C. J., & Carlyon, R. P. (2005). Perception of pitch by people with cochlear hearing loss and by cochlear implant users. In C. J. Plack, R. R. Fay, A. J. Oxenham, et al. (Eds.), *Pitch: Neural Coding and Perception* (pp. 234–277). Springer New York.

Olszewski, C., Gfeller, K., Froman, R., et al. (2005). Familiar melody recognition by children and adults using cochlear implants and normal hearing children. *Cochlear Implants Int, 6*, 123–140.

Padilla, M., Stupak, N., Landsberger, D. M. (2017). Pitch ranking with different virtual channel configurations in electrical hearing. *Hear Res, 348*, 54–62.

Pijl, S., & Schwarz, D. W. (1995a). Intonation of musical intervals by musical intervals by deaf subjects stimulated with single bipolar cochlear implant electrodes. *Hear Res, 89*, 203–211.

Pijl, S., & Schwarz, D. W. (1995b). Melody recognition and musical interval perception by deaf subjects stimulated with electrical pulse trains through single cochlear implant electrodes. *J Acoust Soc Am, 98*(2 Pt 1), 886–895.

Plomp, R. (1976). *Aspects of Tone Sensation: A Psychophysical Study*. Academic Press.

Rader, T., Döge, J., Adel, Y., et al. (2016). Place dependent stimulation rates improve pitch perception in cochlear implantees with single-sided deafness. *Hear Res, 339*, 94–103.

Reiss, L. A., Turner, C. W., Erenberg, S. R., et al. (2007). Changes in pitch with a cochlear implant over time. *J Assoc Res Otolaryngol, 8*, 241–257.

Reiss, L. A., Turner, C. W., Karsten, S. A., et al. (2014). Plasticity in human pitch perception induced by tonotopically mismatched electro-acoustic stimulation. *Neuroscience, 256*, 43–52.

Riss, D., Hamzavi, J. S., Blineder, M., et al. (2014). FS4, FS4-p, and FSP: A 4-month crossover study of 3 fine structure sound-coding strategies. *Ear Hear, 35*, e272–e281.

Rom, D. M. (1990). A sequentially rejective test procedure based on a modified Bonferroni inequality. *Biometrika*, *77*, 663–665.

Schubert, E., & Wolfe, J. (2006). Does timbral brightness scale with frequency and spectral centroid? *Acta Acoust*, *92*, 820–825.

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

Simmons, F. B., White, R. L., Walker, M. G., Mathews, R. G. (1981). Pitch correlates of direct auditory nerve electrical stimulation. *Ann Otol Rhinol Laryngol Suppl, 90*(2 Pt 3), 15–18.

Stakhovskaya, O., Sridhar, D., Bonham, B. H., Leake, P. A. (2007). Frequency map for the human cochlear spiral ganglion: Implications for cochlear implants. *J Assoc Res Otolaryngol, 8*, 220–233.

Stohl, J. S., Throckmorton, C. S., Collins, L. M. (2008). Assessing the pitch structure associated with multiple rates and places for cochlear implant users. *J Acoust Soc Am, 123*, 1043–1053.

Sucher, C. M., & McDermott, H. J. (2007). Pitch ranking of complex tones by normally hearing subjects and cochlear implant users. *Hear Res, 230*, 80–87.

Svirsky, M. A., Silveira, A., Neuburger, H., et al. (2004). Long-term auditory adaptation to a modified peripheral frequency map. *Acta Otolaryngol, 124*, 381–386.

Svirsky, M. A., Silveira, A., Suarez, H., et al. (2001). Auditory learning and adaptation after cochlear implantation: a preliminary study of discrimination and labeling of vowel sounds by cochlear implant users. *Acta Otolaryngol, 121*, 262–265.

Swanson, B., Dawson, P., McDermott, H. (2009). Investigating cochlear implant place-pitch perception with the Modified Melodies test. *Cochlear Implants Int*, *10*, 100–104.

Swanson, B. A., Marimuthu, V. M. R., Mannell, R. H. (2019). Place and temporal cues in cochlear implant pitch and melody perception. *Front Neurosci, 13*, 1266.

Todd, A. E., Mertens, G., Van de Heyning, P., et al. (2017). Encoding a melody using only temporal information for cochlear-implant and normal-hearing listeners. *Trends Hear, 21*, 2331216517739745.

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

Townshend, B., Cotter, N., Van Compernolle, D., et al. (1987). Pitch perception by cochlear implant subjects. *J Acoust Soc Am, 82*, 106–115.

Vandali, A. E., Whitford, L. A., Plant, K. L., et al. (2000). Speech perception as a function of electrical stimulation rate: using the Nucleus 24 cochlear implant system. *Ear Hear, 21*, 608–624.

Vermeire, K., Landsberger, D. M., Schleich, P., Van de Heyning, P. H. (2013). Multidimensional scaling between acoustic and electric stimuli in cochlear implant users with contralateral hearing. *Hear Res, 306*, 29–36.

Vermeire, K., Landsberger, D. M., Van de Heyning, P. H., et al. (2015). Frequency-place map for electrical stimulation in cochlear implants: Change over time. *Hear Res, 326*, 8–14.

Wilson, B. S., Finley, C. C., Lawson, D. T., Zerbi, M. (1997). Temporal representations with cochlear implants. *Am J Otol, 18*, S30–S34.

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

Zhou, N., & Pfingst, B. E. (2016). Evaluating multipulse integration as a neural-health correlate in human cochlear-implant users: Relationship to forward-masking recovery. *J Acoust Soc Am, 139*, EL70–EL75.