Hearing Research 400 (2021) 108136

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Research Paper

Melodic interval perception with acoustic and electric hearing in bimodal and single-sided deaf cochlear implant listeners☆

Emily R. Spitzer[a,*], John J. Galvin III[b], David R Friedmann[a], David M. Landsberger[a]

[a] *New York University Grossman School of Medicine, Department of Otolaryngology-Head and Neck Surgery, 462 1st Avenue, NBV 5E5, New York 10016, NY, USA*
[b] *House Ear Institute, Los Angeles, CA, USA*

A R T I C L E I N F O

Article history:
Received 25 July 2020
Revised 20 November 2020
Accepted 24 November 2020
Available online 29 November 2020

Keywords:
Cochlear implant
Music perception
Single-sided deafness
Bimodal
Melodic interval

A B S T R A C T

Two notes sounded sequentially elicit melodic intervals and contours that form the basis of melody. Many previous studies have characterized pitch perception in cochlear implant (CI) users to be poor which may be due to the limited spectro-temporal resolution and/or spectral warping with electric hearing compared to acoustic hearing (AH). Poor pitch perception in CIs has been shown to distort melodic interval perception. To characterize this interval distortion, we recruited CI users with either normal (single sided deafness, SSD) or limited (bimodal) AH in the non-implanted ear. The contralateral AH allowed for a stable reference with which to compare melodic interval perception in the CI ear, within the same listener.

Melodic interval perception was compared across acoustic and electric hearing in 9 CI listeners (4 bimodal and 5 SSD). Participants were asked to rank the size of a probe interval presented to the CI ear to a reference interval presented to the contralateral AH ear using a method of constant stimuli. Ipsilateral interval ranking was also measured within the AH ear to ensure that listeners understood the task and that interval ranking was stable and accurate within AH. Stimuli were delivered to the AH ear via headphones and to the CI ear via direct audio input (DAI) to participants' clinical processors. During testing, a reference and probe interval was presented and participants indicated which was larger. Ten comparisons for each reference-probe combination were presented. Psychometric functions were fit to the data to determine the probe interval size that matched the reference interval.

Across all AH reference intervals, the mean matched CI interval was 1.74 times larger than the AH reference. However, there was great inter-subject variability. For some participants, CI interval distortion varied across different reference AH intervals; for others, CI interval distortion was constant. Within the AH ear, ipsilateral interval ranking was accurate, ensuring that participants understood the task. No significant differences in the patterns of results were observed between bimodal and SSD CI users.

The present data show that much larger intervals were needed with the CI to match contralateral AH reference intervals. As such, input melodic patterns are likely to be perceived as frequency compressed and/or warped with electric hearing, with less variation among notes in the pattern. The high intersubject variability in CI interval distortion suggests that CI signal processing should be optimized for individual CI users.

1. Introduction

For people with severe-to-profound hearing loss, a cochlear implant (CI) can restore hearing sensation. While the spectro-temporal resolution provided by a CI is adequate to support speech perception under ideal listening conditions, it is not sufficient to support more challenging listening tasks that depend on pitch perception (e.g., talker identification, segregation of competing speech, music perception; Shannon et al. 2004). In CI signal processing, pitch is typically encoded via temporal envelope and electrode place cues, and does not preserve the spectro-temporal fine structure cues needed to support melodic pitch and timbre perception (Oxenham 2013). Even when these cues are provided, improvements in pitch perception are modest at best (e.g., Magnusson 2011; Vandali et al. 2019). Other patient- and device-related considerations (e.g., the electrode-neural interface, channel interaction, and the acoustic-to-electric frequency allocation)

Abbreviations: CI, cochlear implant; AH, acoustic hearing; SSD, single-sided deafness; DAI, direct audio input; st, semitones.

☆ Funding Sources: This work was supported by NIH/NIDCD (R01 DC012152 to DML) and a MED-EL Hearing Solutions grant (DML).

* Corresponding author.
E-mail address: emily.spitzer@nyulangone.org (E.R. Spitzer).

https://doi.org/10.1016/j.heares.2020.108136
0378-5955/© 2020 Elsevier B.V. All rights reserved.

may also contribute to poor and/or distorted pitch perception in CI users.

One of the most basic aspects of music is melody, which depends on not only the direction of pitch changes (melodic contour), but also the size of pitch changes (melodic interval size). Given that pitch perception is generally poor with a CI, it is likely that melodic interval perception is distorted, leading to poor melody perception. Various approaches have been used to characterize and/or quantify musical pitch perception in CI users, including pitch discrimination (e.g., Landsberger & McKay 2005; Goldsworthy 2015), pitch ranking (e.g., Kang et al. 2009; Drennan et al. 2015), familiar melody recognition (e.g., Pijl and Schwarz, 1995; Kong et al. 2004, 2005), melodic pattern discrimination (e.g., Peretz et al. 2003), familiar melody distortion (e.g., Pijl, 1997; Swanson et al. 2009; Luo et al., 2014; Todd et al. 2017; Stupak et al. 2020), and melodic contour identification (e.g., Galvin et al. 2007; Crew et al. 2015). Each of these approaches offer some quantification of attributes that are important for melodic pitch perception, but none directly quantify the distortion to melodic intervals in CI users. For an acoustic input melody, it is useful to know the degree to which melodic intervals are distorted with electric hearing. For example, the upper note in a major 3rd may sound higher-pitched than the lower note with electric hearing, but the size of the pitch change may be distorted such that the interval is perceived as a minor 2nd, major 4th, or some other interval. Based on the acoustic frequency-to-electrode assignment (“frequency allocation”), a given interval will typically be presented across a smaller cochlear extent with electric than with acoustic stimulation, resulting in some degree of melodic interval distortion. However, the degree of this distortion may be further influenced by device- and patient-specific factors including electrode length and placement, broad analysis filters and current spread, size of the cochlea, neural survival, plasticity, and the extent of AH in the non-implanted ear.

Evaluating melodic interval distortion in CI users is not straightforward. Asking a CI user to determine if a change in pitch is perceived as a given melodic interval (e.g., minor 2nd, major 3rd, octave, etc.) requires an accurate concept of that interval. Such central patterns are likely to depend on musical experience before and after implantation, and may greatly differ across CI users depending on signal processing strategies and peripheral factors (e.g., electrode-neural interface). To accurately estimate interval distortion, it is important to have a stable central pattern (an “interval ruler”) that is consistent within and across CI users. Fortunately, CI patients with substantial contralateral acoustic hearing (AH) allow for such an interval ruler. A melodic interval presented to the AH ear can serve as a reference with which to compare intervals presented to the CI ear. The stability of central interval patterns can be measured by comparing reference and probe intervals within the AH ear. Bimodal CI users (limited AH in one ear, CI in the other) and single-sided deaf (SSD) CI users (normal AH in one ear, CI in the other) allow melodic interval perception to be compared between acoustic and electric hearing within the same CI listener.

In this study, melodic interval ranking was measured in bimodal and SSD CI listeners. The goal of the study was to quantify melodic interval distortion in electric hearing, an aspect of music perception that has not been captured by previous studies, but which is important for guiding CI signal processing for music. Interval ranking was compared between the CI ear and contralateral AH ear. Interval ranking was also measured within the AH ear to ensure that listeners understood the task and that the “interval ruler” was stable and accurate within AH. We expected that the frequency allocation would be a primary limiting factor for melodic interval perception with electric hearing.

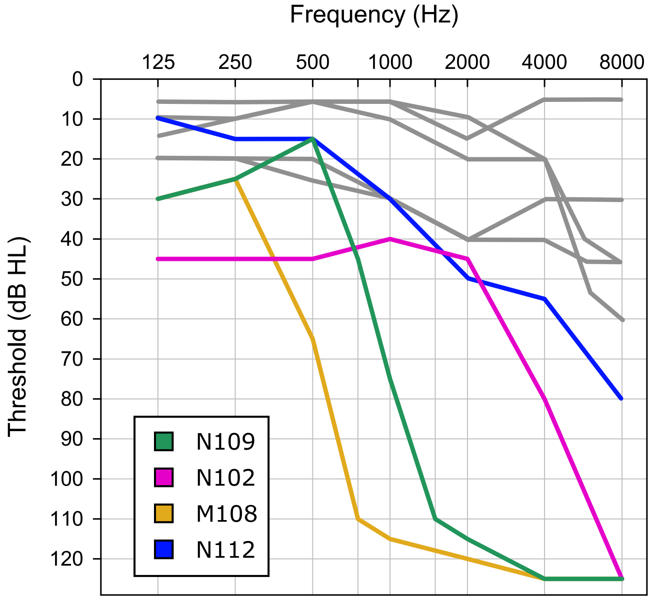

Fig. 1. Audiograms for the non-implanted ear for bimodal (colored lines) and SSD CI listeners (gray lines) who participated in the study.

2. Methods

2.1. Participants

Nine adult, post-lingually deafened CI users participated in this study (4 bimodal, 5 SSD). The mean age at testing was 61.6 years, the mean duration of deafness was 5.2 years, and the mean CI experience was 3.8 years. Two participants (N109 and SSDC1) reported formal musical training, one participant reported informal musical training (SSDN1), and the rest reported no musical experience. Detailed demographic information can be found in Table 1. Fig. 1 shows unaided thresholds for the AH ear; SSD participants are shown in grey and bimodal participants are shown in color. All participants were paid for their participation and provided written informed consent in accordance with Institutional Review Board Procedures (IRB #S14-00809 and #S14-00435) and in accordance with the Declaration of Helsinki.

2.2. Stimuli

Melodic intervals were presented to a reference (AH) ear and a probe (CI) ear. Stimuli were notes consisting of a single pure tone generated using custom Matlab (Mathworks, Natick MA) scripts. Each note was 1 s in duration; the silent duration between successive intervals was 1 second. A 10 ms ramp was applied to the onset and offset of each note. All stimuli were generated with a 44.1 kHz sampling rate and 16-bit depth. The root-mean-square (RMS) amplitude was normalized across all notes. Each interval was comprised of two sequentially presented notes. The “root note,” defined as the lower note in the interval, was always played first, and the “upper note,” which was higher in frequency, was always played second. For each participant, each root note was randomly assigned to either the reference or probe for each test trial. The specific frequencies of the root notes varied across individuals based on the residual AH in the non-implanted ear and the input frequency range of the CI (see Table 1 for details). It was important to test using different root notes to avoid entrainment to a particular frequency, and to accommodate potential differences across CI participants in terms of frequency allocation and the electrode-neural interface. The range of stimuli for most listen-

Table 1
Demographic information and root notes tested for participants.

Participant	Listener type	Age at test (yrs)	CI exp (yrs)	Dur deaf (yrs)	Device	Strategy	# of active electrodes	CI input frequency range (Hz)	Root notes tested Hz (note)
N102	Bimodal	66.4	4.75	7.0	Cochlear Freedom CA	ACE	20	188-7938	247 (B3) 262 (C4)
N109	Bimodal	66.4	0.64	15.0	Cochlear Profile CI532	ACE	22	188-7938	262 (C4) 277 (C#4)
N112	Bimodal	73.0	1.33	4.0	Cochlear Profile CI532	ACE	22	188-7938	247 (B3) 262 (C4)
M108	Bimodal	83.4	10.67	n/a	MED-EL Sonata Medium	FS4	11	100-8500	124 (B2) 131 (C3)
SSD-N1	SSD	71.6	9.18	4.2	Cochlear N512 CI512	ACE	22	188-7938	247 (B3) 262 (C4)
SSD-N8	SSD	50.0	1.92	1.1	Cochlear Profile CI532	ACE	22	188-7938	262 (C4) 294 (D4)
SSD-N11	SSD	42.8	0.58	6.2	Cochlear Profile CI532	ACE	22	188-7938	247 (B3) 262 (C4)
SSD-C1	SSD	34.3	3.70	2.6	AB HiRes 90k Mid Scala	HiRes Optima-P	15	250-8700	262 (C4) 277 (C#4)
SSD-M2	SSD	66.1	1.26	1.3	MED-EL Synchrony Flex 28	FS4-P	12	100-8500	247 (B3) 262 (C4)

ers was approximately 247–2641 Hz; one MED-EL listener was presented with stimuli ranging from 124 to 1250 Hz. All participants were tested with their clinical maps and frequency allocations.

2.3. Procedure

Two reference-probe interval conditions were tested: 1) probe presented to the CI ear, reference presented to the AH ear (contralateral), 2) probe and reference presented only to the AH ear (ipsilateral). The ipsilateral condition was designed to measure the degree of variability in melodic interval ranking within AH, which was expected to be small.

All stimuli were presented using custom software via an audio interface (Tascam US-322). Stimuli were presented to the AH ear via circumaural headphone (Sony MDR-7506) and to the CI ear via direct audio input (DAI). For MED-EL users, the “red” DAI cable was connected between the audio device and the CI processor, which provided a mix of 90% audio input and 10% microphone input. For Cochlear users, participants’ clinical maps were programmed onto a loaner N6 (CP910) processor configured for DAI input only. For Advanced Bionics users, participants’ clinical maps were programmed onto a loaner Harmony processor; the map was configured for DAI input only.

Before testing began, all participants were asked to loudness-balance exemplar reference and probe intervals presented to the AH and CI ears, respectively, at the most-comfortable loudness level. Exemplar stimuli were randomly selected among the 4-st reference vs. 4-st probe, 8-st reference vs. 8-st probe, or 12-st reference vs. 12-st probe comparisons. The reference and probe intervals were presented alternately to the AH and CI ears and the participant adjusted the output volume of each channel of the audio device until the loudness was similar across ears. After these adjustments, participants were not allowed to adjust the volume of either output for the remainder of the experiment.

During each trial of testing, a reference interval was presented to the AH ear and a probe interval was presented to the probe ear (contralateral CI ear or ipsilateral AH ear, depending on the test condition); the reference interval was always presented first. The subject indicated which interval was larger by clicking on one of two response boxes onscreen (“Interval 1 larger” or “Interval 2 larger”). Subjects were allowed to repeat intervals as many times as they liked prior to making a judgement. Each reference-probe comparison was measured a total of 10 times across 3 test blocks (four comparisons in block 1, three comparisons in block 2, and three comparisons in block 3). Each reference interval condition (4, 8, or 12 semitones (st)) and each reference ear condition (contralateral or ipsilateral) was tested in a separate block. Thus, each participant completed a total of 18 test blocks for each listening condition (3 reference interval conditions x 2 reference ear conditions x 3 test blocks). The order of test blocks was randomized across participants. Sigmoid functions were fit to the interval ranking data for each reference interval. The interval size at the midpoint of the sigmoid function was considered to be the “match” to the reference interval. For the AH vs. CI comparison, the reference interval presented to the AH ear was 4, 8, or 12 st, the minimum probe interval presented to the CI ear was 4 st and the maximum probe interval was >20 st (often >40 st), except for SSDN8, where the minimum was 2 st and the maximum was 18 st. For the AH vs. AH comparison, the reference and probe intervals presented to the AH ear were 2, 4, 6, or 8 st.

3. Results

Fig. 2 shows the percentage of trials when the probe CI interval was judged to be larger than the reference AH interval; note that data were collapsed across root notes, which were randomly varied across ears during each test trial. The range of CI intervals was adjusted on individual basis to reduce testing time by minimizing the number of redundant trials after the sigmoid function reached 100%. Sigmoid functions were fit to the data (lines in Fig. 2). Sigmoid functions shift to the right with increasing reference interval, suggesting that the CI interval ranking increased with increasing reference interval.

The 50% point of the sigmoid functions shown in Fig. 2 was considered to be the CI interval size that matched the AH reference interval. The ratio between the upper note of the matched CI interval and the upper note of the AH reference interval was considered to be the degree of CI interval distortion, relative to the AH reference. Fig. 3 shows the CI distortion ratio (left y-axes) relative to the 4-, 8-, and 12-st reference intervals; data were averaged across root note conditions. Values > 1 indicate that the matched CI interval was larger than the AH reference; values equal to 1 indicate a perfect match between the CI probe and AH reference. The mean CI distortion ratio was 1.87, 1.70, and 1.67 for the 4-, 8-, and 12-st reference intervals, respectively. As shown by the upper and lower bounds of the 95% confidence interval (gray shaded area in each panel), the CI ratios were significantly larger than 1 for the 4- and 12-st references (dashed black line = 1), but not for the 8-st reference, where the lower bound was just below 1. A repeated-measures analysis of variance (RM ANOVA) showed

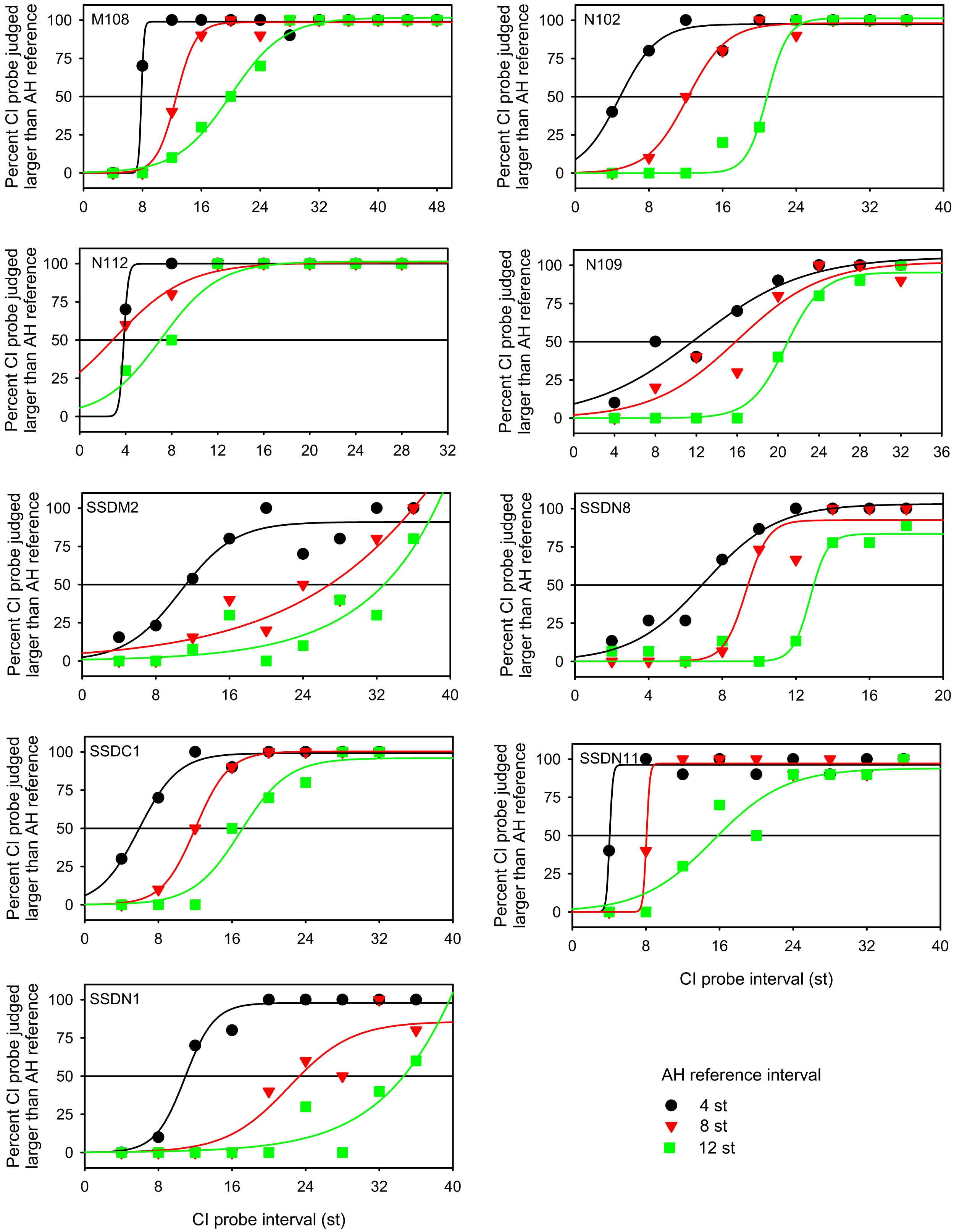

Fig. 2. Percent of trials that the CI probe interval was judged to be higher than the reference interval presented to the AH ear (contralateral), as a function of CI probe interval. Data are shown for the 4-st (black), 8-st (red), and 12-st reference intervals (green). The lines show sigmoid fits to the data. The horizontal line shows 50% correct, and the intersection between the sigmoid fit and the horizontal line was deemed the CI interval that matched the AH reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

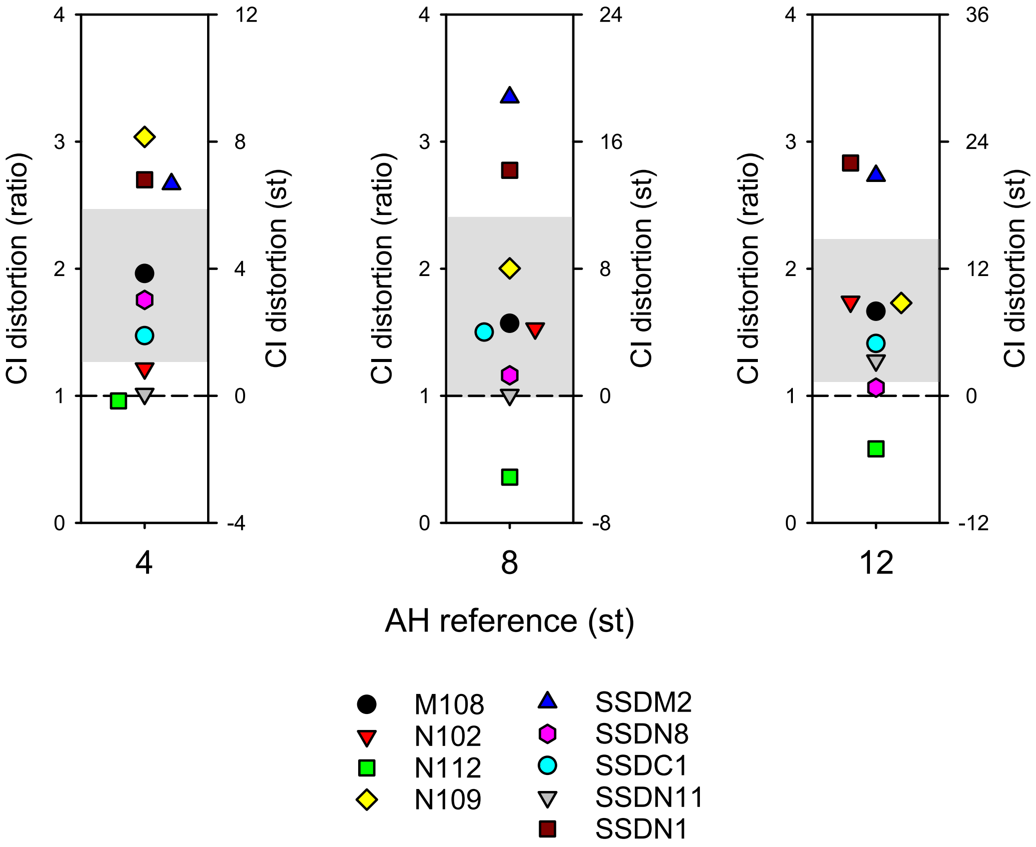

Fig. 3. CI interval distortion relative to the contralateral 4-, 8-, and 12-st AH reference intervals. In each panel, the left y-axis shows the ratio between the CI matched interval (i.e., the 50% correct point on the sigmoid functions in Fig. 2) and the AH reference. The dashed black line (equal to 1) represents a perfect match between the CI matched interval and the AH reference. The gray shaded area shows the upper and lower bounds of the 95% confidence interval of the mean interval. The right y-axis shows the CI distortion in st relative to the AH reference. The dashed black line (equal to 0) represents a perfect match between the CI interval and the AH reference.

no significant difference in CI distortion ratios across AH reference intervals [F(2,16) = 0.9, p = 0.430].

CI distortion was also expressed in terms of the st difference between the size of the matched CI interval and the AH reference interval (right y-axes of Fig. 3). Note that the right y-axis range increases with AH reference interval size. Values $>$ 0 indicate that the matched CI interval was larger than the AH reference; values equal to 0 indicate a perfect match between the CI probe and AH reference. The mean CI distortion (in terms of st) was 3.46, 5.56, and 8.05 st for the 4-, 8-, and 12-st AH reference intervals, respectively. A RM ANOVA showed a significant effect of AH reference interval [F(2,16) = 27.11, $p < 0.001$], suggesting the CI distortion in st was not the same for each reference interval.

Similar to Fig. 2, Fig. 4 shows the percentage of trials when the probe interval was judged to be larger than the reference interval for ipsilateral presentation within the AH ear. The reference and probe intervals were 2-, 4-, 6-, and 8-st. Sigmoid functions were fit to the data, and the 50% point on the sigmoid function was considered to be the perceptual match to the reference. The mean ratio between the matched AH probe and AH reference intervals was 1.10, 0.94, 0.97, and 0.96 for the 2-, 4-, 6- and 8-st reference intervals, respectively. The matched interval was within the 95% confidence intervals for all reference intervals, indicating no significant difference between the matched ratio and the reference ratio of 1. The mean difference (in terms of st) between the matched AH probe and AH reference interval was 0.25, −0.23, −0.16, and −0.29 st for the 2-, 4-, 6- and 8-st reference intervals, respectively.

4. Discussion

The present study investigated melodic interval perception in CI users with good low-frequency contralateral AH thresholds. For most participants, the interval presented to the CI ear needed to be larger to match the reference interval presented to the AH ear. This suggests that melodic interval perception with a CI is distorted and intervals are typically perceived to be smaller than intervals input to the acoustic ear.

4.1. Cues available for melodic interval perception with electric hearing

In CIs, pitch can be coded by spectral cues (stimulation patterns across electrodes) and/or temporal cues in the amplitude modulation and/or the stimulation rate (e.g., Zeng 2002). In the present study, the pure-tone stimuli were designed to elicit spectral cues, without the temporal modulation cues that would be available with “real” musical instruments. However, some stimulation rate cues may have been available for users of Advanced Bionics and MED-EL devices. Fig. 5 shows electrodograms produced by the Advanced Bionics, Cochlear, and MED-EL devices for some of the notes used to comprise melodic intervals. Thus, to create a 4-, 8-, or 12-st melodic interval, the root note C4 (262 Hz) was paired with notes E4 (330 Hz), G#4 (415 Hz), and C5 (524 Hz), respectively. The electrodograms were generated using default parameters (e.g., frequency allocation and stimulation rate) for the Fidelity 120 (Advanced Bionics), ACE (Cochlear), and FS4 (MED-EL)

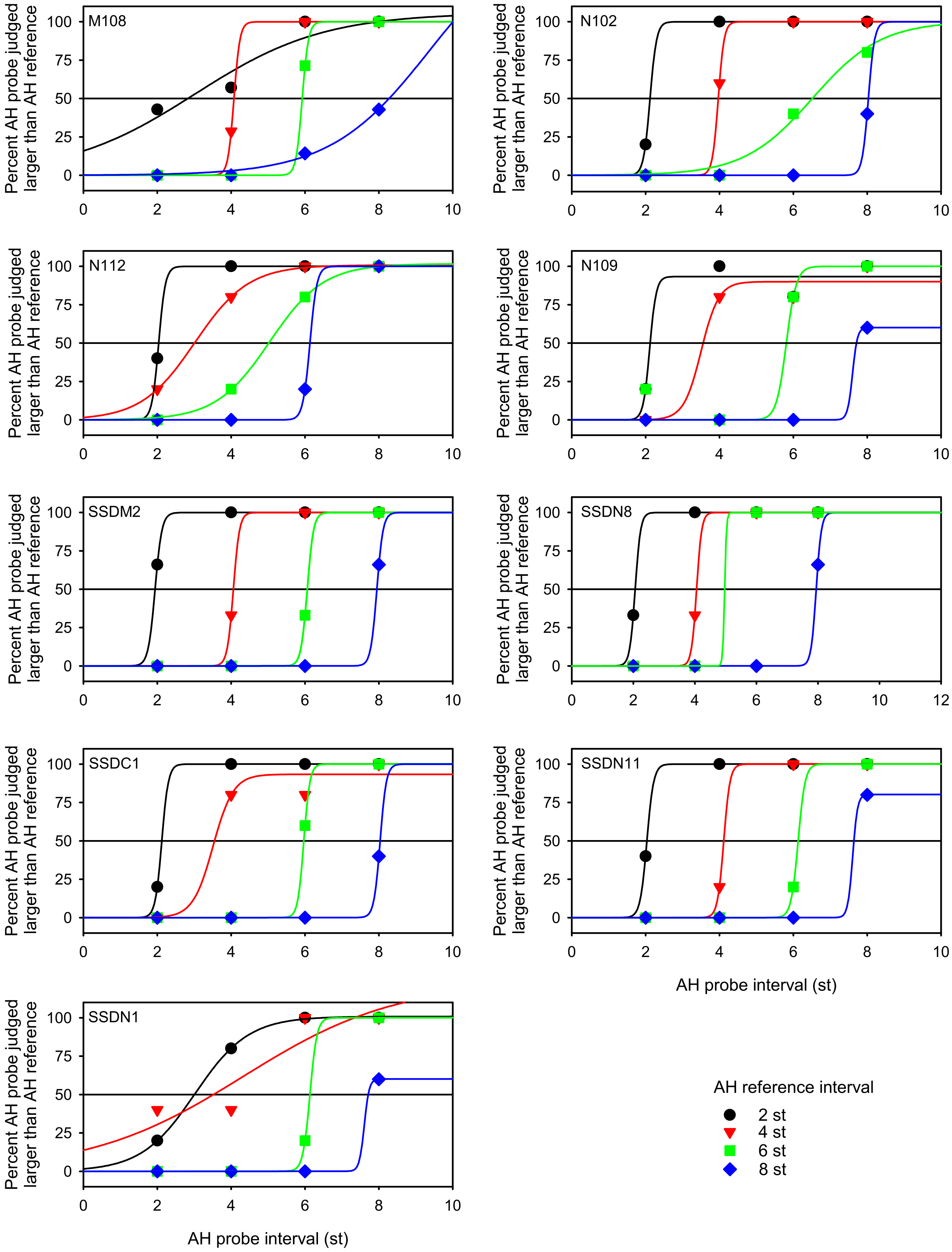

Fig. 4. Percent that the AH probe interval was judged to be higher than the reference interval presented to the AH ear (ipsilateral presentation), as a function of AH probe interval. Data are shown for the 2-st (black), 4-st (red), 6-st (green), and 8-st (blue) reference intervals. The lines show sigmoid fits to the data. The horizontal line shows 50% correct, and the intersection between the sigmoid fit and the horizontal line was deemed the CI interval that matched the AH reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

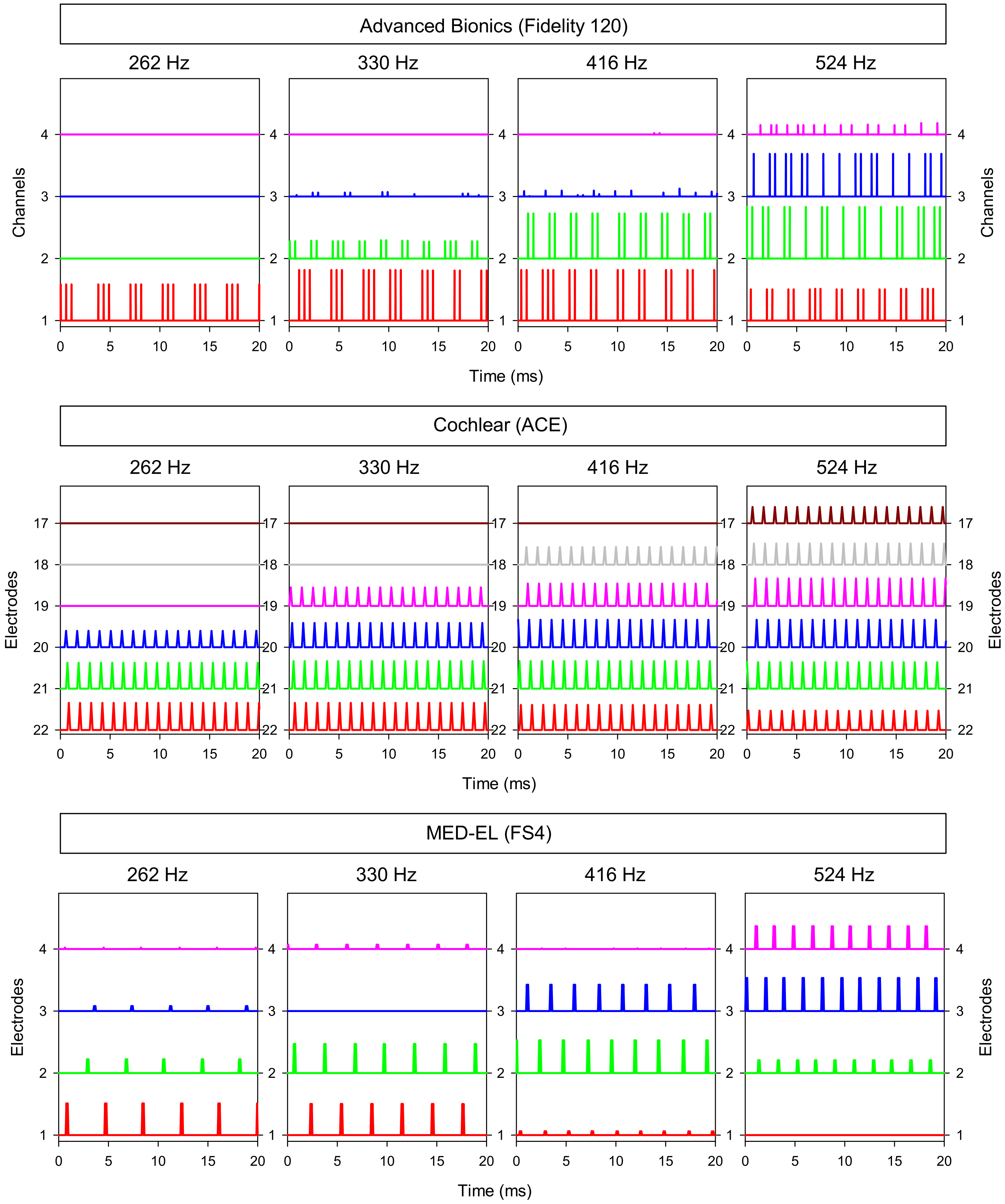

Fig. 5. Electrodograms for each note that comprised the reference intervals. The columns show the root note (C4, 262 Hz), 4-st shift (E4, 330 Hz), 8-st shift (G#4, 415 Hz), and 12-st shift (C5, 524 Hz). Electrodograms are shown for Advanced Bionics (top), Cochlear (middle), and MED-EL devices (bottom). The electrodograms were generated using the clinical default parameters for each device (e.g., frequency allocation, stimulation rate, processing strategy). Data are shown only for the most apical electrodes stimulated by the different notes.

signal processing strategies. In order to show the greatest detail, the number of channels presented are limited to those providing substantial stimulation, resulting in 4 channels displayed for Advanced Bionics and MED-EL devices and 6 channels for Cochlear devices. The output of each electrode is represented directly as a channel for Cochlear and MED-EL devices. As the Advanced Bionics Fidelity 120 and Optima strategies use “virtual channels” created by simultaneous stimulation of adjacent electrodes, the Advanced Bionics plot is represented in terms of virtual channel pairs (i.e., channel 1 represents simultaneous pulses on electrodes 1 and 2, channel 2 represents simultaneous pulses on electrodes 2 and 3, etc.). For all three devices, the spectral pattern generally shifts towards the base of the cochlea (e.g., higher along the y-axes) as the frequency of the notes increases. As shown in Fig. 5, multiple electrodes were stimulated in response to the acoustic pure-tone input, due to the broad nature of the frequency analysis filters or fast-Fourier transform. Note that when the current spread associated with electric stimulation is considered, the spread of excitation may be even greater than suggested by the electrodograms.

The temporal stimulation patterns differed substantially across devices. As described in Swanson et al. (2009) and Stupak et al. (2020), the Cochlear device provided a fixed stimulation rate for each channel providing no temporal cues to the input frequency. The MED-EL FS4 and FS4p strategies provide packets of pulses at a rate corresponding to the input frequency on the first 4 electrodes (Riss et al. 2014), which represent all of the stimuli in this experiment, providing a reliable temporal cue in addition to the spectral cues. The Advanced Bionics HiRes strategies (including Fidelity 120 and Optima) half-wave rectify the outputs of each channel, resulting in a gated high-rate pulse train. For frequencies above 306 Hz, the gating frequency matches the input note frequency whereas input frequencies below 306 Hz are gated at 306 Hz. As a result, an accurate temporal cue is provided for most of the stimuli used in this experiment, but the 262 Hz root note in this example would be represented with 306 Hz temporal information (see Fig. 9 of Stupak et al. 2020). For further details regarding how different CI signal processing strategies provide temporal information in response to pure-tones, see the Appendix in Stupak et al. (2020).

While temporal cues might have been available for users of Advanced Bionics and MED-EL devices, they do not appear to have provided any clear advantage among the limited number of CI participants. When both temporal and place cues are available, it remains unclear how they collectively contribute to interval perception. While it has been demonstrated that temporal and place pitch are independent percepts (e.g., Tong et al. 1983; McKay et al. 2000; Landsberger et al. 2018), combining the two cues can alter perception of pitch height (Luo et al. 2012). With more complex stimuli (e.g., real musical instruments), temporal modulation cues would also be available for melodic pitch perception. However, it is unclear how much temporal rate and/or modulation cues contribute in the presence of coarse but dynamic spectral envelope cues. For example, temporal modulation cues contributed strongly to SSD CI users’ perception of harmonic intervals (i.e., two notes sounded simultaneously) played by a MIDI piano (Spitzer et al. 2019).

For most CI devices, the acoustic input frequency range is mapped to a cochlear region that is limited by the extent of the electrode array. Depending on the electrode insertion depth, there may also be a frequency mismatch between the acoustic input and electrode place (Landsberger et al. 2015). With only 12–22 electrodes maximally available, there is a hard limit to melodic interval resolution within electric hearing. Landsberger et al. (2015) reported that mean degrees of separation between adjacent electrodes was, on average, 17, 24, and 43º across Cochlear (Contour Advance), Advanced Bionics (1J), and MED-EL (Flex 28) electrodes, respectively. In Fig. 6, these electrode spacing data are expressed in st (x-axis) relative to the most apical electrode position. The y-axes show the spacing between the center frequencies of the default frequency analysis bands, again expressed in st relative to the most apical frequency band. The diagonal lines indicate that the spacing between electrodes and frequency bands is the same. When the slope of a region is steeper than the diagonal reference line, there is frequency compression between the acoustic input and the electric stimulation pattern. Such frequency compression is evident for the apical region (where the present stimuli were presented) for all three devices. For Cochlear and MED-EL devices, there is reduced frequency compression in the middle and basal regions. Aligning the frequency allocation to electrode spacing would reduce the frequency compression that occurs with most clinical CI signal processors.

4.2. Melodic interval distortion across acoustic and electric hearing

The ipsilateral AH reference-probe condition was important to establish the interval resolution (the “interval ruler”) within the AH ear, as well as to demonstrate understanding of the task. When listening only with the AH ear, participants exhibited accurate interval perception (Fig. 4), suggesting that listeners understood the task, and that the perceived interval was very similar to the reference interval within the AH ear for most reference intervals and most subjects. There was no difference in interval distortion between SSD and bimodal listeners, suggesting sufficient acoustic audibility within the range of root notes and intervals tested.

While most participants exhibited melodic interval distortion with the CI ear relative to the contralateral AH reference, there was considerable inter-subject variability as well as intra-subject variability across reference intervals. As shown in Fig. 3, some participants exhibited stable distortion across reference intervals (e.g., M108, SSDN1, SSDN11), while others exhibited varying degrees of distortion across reference intervals (e.g., N109, N102, SSDN8). Some participants (e.g., N112, SSDN11, SSDN8) even exhibited near-normal performance (ratios close to 1), at least for some reference intervals. For the 8- and 12-st reference intervals, N112 the matched interval size was smaller than the AH reference. Note however that N112 exhibited similar tendencies to underestimate probe interval size even when the reference and probe were presented ipsilaterally to the AH or CI ear (Fig. 4). There were no notable differences in the degree of distortion between participants who reported musical training (N109, SSDC1 and SSDN1) and those who did not. Overall, the degree of distortion appeared to be very listener-dependent.

The slope of the sigmoid function fit to the data also varied significantly across participants and reference intervals (Fig. 2). In general, the slope became shallower with increasing reference interval size, suggesting greater uncertainty for large intervals. One factor that may have contributed to the steepness of the sigmoid functions is the range of CI probe intervals relative to the AH reference intervals. In general, probe intervals ranged from 4 st to more than 20 st, and were often greater than 40 st. As such, there were fewer probe intervals that were smaller than the reference intervals, and most were larger. This raises the possibility of response bias towards larger probe intervals, especially for the 4-st reference. In Fig. 3, data from M108, N112, and SSDN11 may suggest such bias, as the sigmoid fit becomes sharper as the reference interval becomes smaller. Data for the remaining participants are more variable, with no clear effect of reference interval on the steepness of the sigmoid fits. Note that for ipsilateral presentation to the AH ear (Fig. 4), both the reference and probe intervals were 2-, 4-, 6-, and 8-st; as such, there were differing numbers of probe intervals that were smaller or larger than the reference intervals, depending on the specific reference. The slopes of the sigmoid fits were generally steep across reference intervals. This suggests lim-

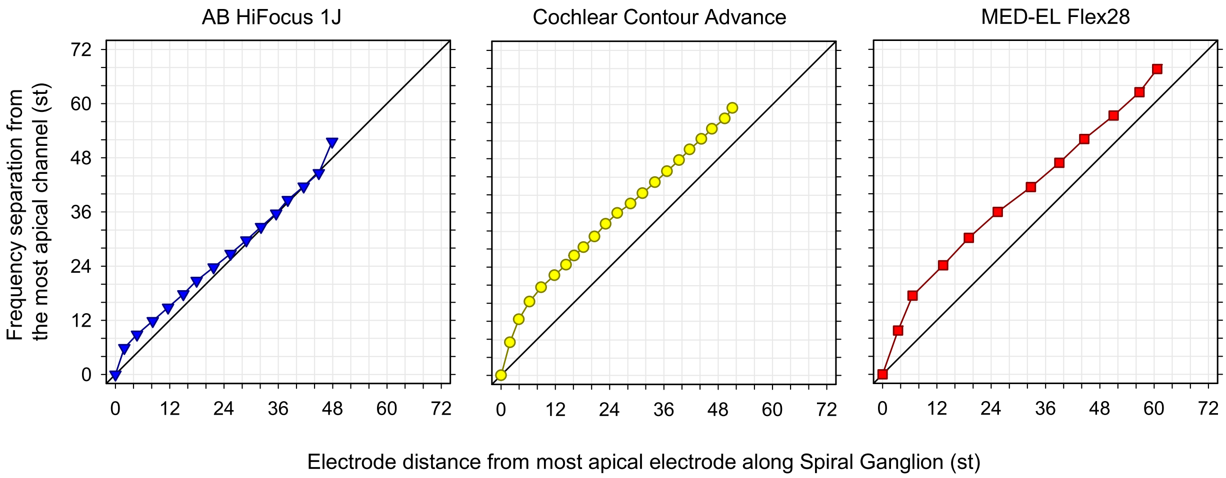

Fig. 6. Frequency separation (in st) of analysis bands relative to the most apical band, as a function of the electrode separation (in st) relative to the most apical electrode. Frequency separation was estimated according to the center frequencies of the analysis bands for the default acoustic-to-electric frequency allocations for each device. Electrode separation was estimated using data from Stakhovskaya et al. (2007) and Landsberger et al. (2015). The grid has 4-st resolution. The diagonal line indicates equal spacing between the frequency analysis channels and the electrodes; data above the diagonal indicated frequency compression of the input acoustic signal onto the electrode array.

ited bias, as well as confidence in the interval ranking task and certainty regarding interval size judgements.

It is also possible that interval ranking may have been more difficult for large intervals. Interval perception has shown to be more difficult for larger than for smaller intervals for normal-hearing (Russo et al., 2005) and CI listeners (Luo et al., 2014). Smaller intervals also seem to be more prevalent in popular music. For example, for familiar melodies often used to test melodic pitch perception in CI listeners (Kong et al. 2004), the intervals between successive notes are often between 1 and 4 st, and rarely more than 8 st. For the melodic contour identification tasks in CI listeners by Galvin and colleagues (Galvin et al. 2007), the intervals between successive notes ranged from 1 to 5 st. In general, there may be a bias towards smaller intervals within commonly heard music that may contribute towards interval judgements.

4.3. Advantages of the interval ranking task

Previous studies have investigated melodic pitch perception in CI listeners using simple pitch ranking (Kang et al. 2009), familiar melody recognition (Kong et al. 2004), distorted melodic patterns (Todd et al. 2017), and melodic contour identification tasks (Galvin et al. 2007). While melodic pitch perception has been characterized and quantified in different ways across these tasks, CI performance is generally limited by the common factor of poor spectral resolution and/or spectral warping, due to the relationship between the coarse frequency allocation and the electrode-neural interface. As the physical distortions along the cochlea as well as the state of adaptation vary across CI listeners, it is difficult to provide a single correction across listeners.

The present interval ranking task directly quantifies the degree of interval distortion, rather than inferring the distortion from pitch ranking or melodic pattern perception. Listeners were asked to make judgements regarding relative interval size that were not constrained by melodic context (e.g., familiar melody), and were possibly more relevant to melody perception than simple pitch discrimination or ranking, where interval size is not explicitly considered. The data from the present study show that much larger frequency differences were needed with electric hearing to match the reference interval with AH, consistent with Stupak et al. (2020). The data also quantify differences in perception across intervals and/or across CI listeners.

Another novel aspect of the present methodology was the ability to compare melodic interval perception between acoustic and electric hearing within the same bimodal or SSD CI listener. By presenting the reference interval to the AH ear, melodic interval perception with electric hearing could be effectively “calibrated.” This approach is different from previous acoustic versus electric pitch-matching experiments with bimodal and SSD CI listeners (Reiss et al. 2014, 2015; Vermeire et al. 2015). In these studies, an electrode is typically selected as a reference and the frequency of a pure tone presented to the AH ear is adjusted to match the “pitch” of the reference electrode. “Pitch” is in quotes here because the sound quality difference between acoustic and electric hearing is so substantial as to suggest that listeners may be adjusting the pitch in AH to match the timbre in electric hearing (McDermott et al. 2009; Carlyon et al. 2010). It is possible that uncertainty resulting from differences in timbre across ears contributed to the sometimes shallow psychometric functions observed in the present study. Furthermore, pitch-matches across acoustic and electric hearing can be unstable and may even evolve with increasing CI experience (Reiss et al. 2015; Peters et al. 2016). While pitch-matching data may indicate idiosyncrasies across electrodes and/or CI listeners, they do not necessarily contextualize this pitch information within music. The present melodic interval perception task provides this context.

4.4. Limitations to the study

There are several limitations to the present study. Pure tone stimuli were used as the “instrument,” rather than more complex stimuli such as piano samples (as used in a related study by Spitzer et al. 2019). Pure tones were used to avoid the distortions between harmonics that would accompany interval distortions. With more complex stimuli, both spectral and temporal cues would be available with electric hearing, which might alter the present pattern of results and be more representative of CI melodic interval perception in everyday listening.

In order to ensure acoustic audibility for bimodal CI users (who have limited frequency range) and SSD CI users (who have normal frequency range), the root notes of the stimuli were restricted to a low frequency range. It is unclear whether the patterns of distortion would be similar at higher frequencies. Because it was necessary to use a low root note to accommodate the limited AH in bimodal listeners, only ascending intervals were tested; it is unclear how the present interval ranking data might change with descending intervals. To accommodate the limited AH in bimodal listeners, the two root notes differed only by 1 semitone (see Table 1).

Within AH, this difference would have been sufficient to produce a change in pitch, as evidenced by the AH-only ipsilateral pitch ranking data (see Fig. 4). Within the CI ear, it is likely that the different root notes sounded similar in pitch, due to the broad analysis filters in the frequency allocation (see the electrodograms in Fig. 5). An alternative would have been to modify the root notes in the CI ear to be very different (e.g., C4 and F5), such that the stimulation pattern would be different from trial to trial. The potential downside to this approach is that the overall pitch range would be quite different between the AH ear (where low frequencies were used to accommodate bimodal listeners) and the CI ear, making the interval ranking task more difficult and possibly more susceptible to tracking only the higher note in each interval.

As noted above, the probe intervals presented to the CI were generally larger than the reference intervals presented to the AH ear, resulting in potential response bias. This bias towards probe intervals being larger than reference intervals resulted in some participants who did not exhibit an interval judgement below the 50% point, especially for the 4-st reference (e.g., N112). This could be remedied by presenting equal numbers of probe intervals above and below the reference interval. However, CI listeners generally have difficulty discriminating stimuli that differ between 1 and 3 st (Kang et al. 2009; Gfeller et al. 2002), due to the coarse spectral resolution. As such, it would be difficult to generate probe intervals less than 4 st, as the component notes may not be discriminable.

Finally, there were a small number of CI users that participated in the study ($n = 9$). While a greater number of participants is always desirable, there are limited numbers of CI users with substantial AH in the non-implanted ear; the number of SSD CI users is especially limited. However, it is likely that a greater number of CI participants would only add to the high inter-subject variability observed in the present study. Indeed, the present data indicate that CI signal processing will likely need to be optimized for individual CI users, with no “one-size-fits-all” solution.

4.5. Clinical implications

The present data suggest that melodic interval perception is typically frequency-compressed and distorted within electric hearing. When listening to real music with a CI, this implies that melodic patterns will vary much less than the acoustic input to the CI, resulting in a flatter and/or distorted pattern, consistent with previous CI melodic pattern perception data (e.g., Swanson et al. 2009; Todd et al. 2017; Stupak et al. 2020). Furthermore, this suggests that not only melodic intervals but harmonic structures will also be distorted in that harmonic structure also depends on the perception of interval relationships. One critical finding in this study is the variability in melodic interval perception across CI listeners. This suggests that frequency allocations may need to be optimized for individual CI users. While the interval distortion ratios were largely similar across reference intervals, the st distortion increased with reference interval (right axes in Fig. 3). Also, while it is possible to modify the frequency allocation to better preserve melodic intervals, it is unclear how this modification would affect speech perception or sound quality.

Modifying the frequency allocation alone may not be beneficial unless the underlying spectral resolution is improved. As shown in Fig. 6, there is limited interval resolution due to the limited number of implanted electrodes. One approach to improve this underlying spectral resolution is to provide current-steered virtual channels between the physical electrodes, as in Advanced Bionics’ Fidelity 120 and Optima signal processing strategies. These strategies increase the number of sites of stimulation from 16 (HD-CIS) to 120 (Fidelity 120) or 135 (Optima). However, studies have yet to show substantial or significant advantages in speech or music performance with virtual channels (Berenstein et al. 2008; Buechner et al. 2008). The lack of benefit for virtual channels is likely due to the broad current spread associated with multi-channel, monopolar stimulation, which may overwhelm any putative gains in spectral resolution associated with current steering (e.g., Landsberger & Srinivasan 2009). Also, the number of salient virtual channels depends strongly on the patterns of nerve survival; if there are too few healthy neurons between adjacent electrodes, current steering will have no benefit.

Finally, given the present interval distortion data, bimodal and SSD CI users would assumedly perceive input melodic patterns quite differently between acoustic and electric hearing. The CI melodic interval distortion, combined with the likely inter-aural frequency mismatch, would be expected to result in very different stimulation patterns across ears that might interfere with music perception and enjoyment. However, this does not seem to be the case. Bimodal CI users regularly exhibit better music perception and enjoyment with combined acoustic and electric hearing (Sucher & McDermott 2009; Landsberger et al. 2020). SSD CI users, who have a broad frequency range in both acoustic and electric hearing, report that music is significantly more enjoyable when listening with combined acoustic and electric hearing than listening with AH alone (Landsberger et al. 2020). This suggests some binaural benefit for combined acoustic and electric hearing that may not depend on quality or resolution of the stimulation patterns in the CI ear. However, optimizing CI signal processing in light of contralateral AH may further improve the binaural benefit.

4.6. Conclusions

Melodic interval perception was measured in bimodal CI and SSD CI listeners. Reference intervals were presented to the AH ear and probe intervals were presented to the CI ear. Listeners were asked whether the probe was larger than the reference. As a control condition, melodic interval perception was also measured when the reference and probe intervals were presented within the AH ear. Major findings include:

- On average, the matched CI interval was 1.74 times larger than the reference interval presented to the AH ear. The CI interval distortion ratio was not significantly affected by reference interval size, but the CI distortion in st increased with reference interval size. There was great variability in CI interval distortion among participants. The present data suggest that music presented to CI listeners is perceived as frequency-compressed, with reduced variation in pitch across melodic patterns.
- For ipsilateral presentation of the reference and probe intervals in the AH ear, there was nearly no distortion, suggesting that participants could perform the task reliably and that AH provided a stable “interval ruler” with which to measure melodic interval distortion in electric hearing.
- The clinical frequency allocation is a primary limitation to melodic interval perception, but other factors such as the electrode-neural interface may also contribute to melodic interval distortion with electric hearing. Adjusting the frequency allocation may improve perception of small melodic intervals $<$ 4 st.

Author Statement

Emily R. Spitzer: Data collection, software, data analysis, manuscript preparation; John J. Galvin III: Experimental design, data analysis, manuscript preparation; David R Friedmann: Experimental design, manuscript preparation; David M. Landsberger: Experimental design, data analysis, manuscript preparation.

Acknowledgments

We would like to thank all of the participants for their help with this research.

References

Berenstein, C.K., Mens, L.H.M., Mulder, J.J.S., et al., 2008. Current steering and current focusing in cochlear implants: comparison of monopolar, tripolar, and virtual channel electrode configurations. Ear Hear. 29, 250.

Buechner, A., Brendel, M., Krüeger, B., et al., 2008. Current Steering and results from novel speech coding strategies. Otol. Neurotol. 29, 203–207.

Carlyon, R.P., Macherey, O., Frijns, J.H.M., et al., 2010. Pitch comparisons between electrical stimulation of a cochlear implant and acoustic stimuli presented to a normal-hearing contralateral ear. JARO 11, 625–640.

Crew, J.D., Galvin III, J.J., Landsberger, D.M., et al., 2015. Contributions of electric and acoustic hearing to bimodal speech and music perception. PLOS One 10, e0120279.

Drennan, W.R., Oleson, J.J., Gfeller, K., et al., 2015. Clinical evaluation of music perception, appraisal and experience in cochlear implant users. Int. J. Audiol. 54, 114–123.

Galvin, J.J., Fu, Q.-J., Nogaki, G., 2007. Melodic contour identification by cochlear implant listeners. Ear Hear. 28, 302–319.

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.

Goldsworthy, R.L., 2015. Correlations between pitch and phoneme perception in cochlear implant users and their normal hearing peers. JARO 16, 797–809.

Kang, R., Nimmons, G.L., Drennan, W., et al., 2009. Development and validation of the university of washington clinical assessment of music perception test. Ear Hear. 30, 411–418.

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.

Kong, Y.-Y., Stickney, G.S., Zeng, F.-G., 2005. Speech and melody recognition in binaurally combined acoustic and electric hearing. J. Acoust. Soc. Am. 117, 1351–1361.

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–EL514.

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., 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, S., Roland, J.T., 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., 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.

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.

Magnusson, L., 2011. Comparison of the fine structure processing (FSP) strategy and the CIS strategy used in the MED-EL cochlear implant system: speech intelligibility and music sound quality. Int. J. Audiol. 50, 279–287.

McDermott, H., Sucher, C., Simpson, A., 2009. Electro-acoustic stimulation. AUD 14, 2–7.

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.

Oxenham, A.J., 2013. Revisiting place and temporal theories of pitch. Acoust. Sci. Technol. 34, 388–396.

Peretz, I., Champod, A.S., Hyde, K., 2003. Varieties of musical disorders. Ann. N. Y. Acad. Sci. 999, 58–75.

Peters, J.P.M., Bennink, E., Grolman, W., et al., 2016. Electro-acoustic pitch matching experiments in patients with single-sided deafness and a cochlear implant: Is there a need for adjustment of the default frequency allocation tables? Hear. Res. 342, 124–133.

Pijl, S., 1997. Labeling of musical interval size by cochlear implant patients and normally hearing subjects. Ear Hear. 18, 364–372.

Pijl, S., Schwarz, D.W.F., 1995. Melody recognition and musical interval perception by deaf subjects stimulated with electrical pulse trains through single cochlear implant electrodes. J. Acoust. Soc. Am. 98, 886–895.

Reiss, L.A.J., 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.

Reiss, L.A.J., Ito, R.A., Eggleston, J.L., et al., 2015. Pitch adaptation patterns in bimodal cochlear implant users: over time and after experience. Ear Hear. 36, e23–e34.

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.

Russo, F.A., Thompson, W.F., 2005. The subjective size of melodic intervals over a two-octave range. Psychon. Bull. Rev. 12, 1068–1075.

Shannon, R.V., Fu, Q.-J., Galvin, J., 2004. The number of spectral channels required for speech recognition depends on the difficulty of the listening situation. Acta Otolaryngol. Suppl. 50–54.

Spitzer, E.R., Landsberger, D.M., Friedmann, D.R., et al., 2019. Pleasantness ratings for harmonic intervals with acoustic and electric hearing in unilaterally deaf cochlear implant patients. Front. Neurosci. 13.

Sucher, C.M., McDermott, H.J., 2009. Bimodal stimulation: benefits for music perception and sound quality. Cochlear Implants Int. 10, 96–99.

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

Stakhovskaya, O., Sridhar, D., Bonham, B.H., et al., 2007. Frequency map for the human cochlear spiral ganglion: implications for cochlear implants. J. Assoc. Res. Otolaryngol. 8, 220–233.

Stupak, N., Todd, A.E., Landsberger, D.M., 2020. Place-pitch interval perception with a cochlear implant. Ear Hear. doi:10.1097/AUD.0000000000000922.

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., et al., 1983. Psychophysical studies evaluating the feasibility of a speech processing strategy for a multiple-channel cochlear implant. J. Acoust. Soc. Am. 74, 73–80.

Vandali, A., Dawson, P., Au, A., et al., 2019. Evaluation of the optimized pitch and language strategy in cochlear implant recipients. Ear Hear. 40, 555–567.

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.

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