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Research paper

Electric-acoustic pitch comparisons in single-sided-deaf cochlear implant users: Frequency-place functions and rate pitch

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ABSTRACT

Eight cochlear implant users with near-normal hearing in their non-implanted ear compared pitch percepts for pulsatile electric and acoustic pure-tone stimuli presented to the two ears. Six subjects were implanted with a 31-mm MED-EL FLEX$^{\mathrm{SOFT}}$ electrode, and two with a 24-mm medium (M) electrode, with insertion angles of the most apical contacts ranging from 565° to 758°. In the first experiment, frequency-place functions were derived from pure-tone matches to 1500-pps unmodulated pulse trains presented to individual electrodes and compared to Greenwood's frequency position map along the organ of Corti. While the overall median downward shift of the obtained frequency-place functions (-0.16 octaves re. Greenwood) and the mean shifts in the basal ($<240°$; -0.33 octaves) and middle (-0.35 octaves) regions were statistically significant, the shift in the apical region ($>480°$; 0.26 octaves) was not. Standard deviations of frequency-place functions were approximately half an octave at electrode insertion angles below 480°, increasing to an octave at higher angular locations while individual functions were gradually leveling off.

In a second experiment, subjects matched the rates of unmodulated pulse trains presented to individual electrodes in the apical half of the array to low-frequency pure tones between 100 Hz and 450 Hz. The aim was to investigate the influence of electrode place on the salience of temporal pitch cues, for coding strategies that present temporal fine structure information via rate modulations on select apical channels. Most subjects achieved reliable matches to tone frequencies from 100 Hz to 300 Hz only on electrodes at angular insertion depths beyond 360°, while rate-matches to 450-Hz tones were primarily achieved on electrodes at shallower insertion angles. Only for electrodes in the second turn the average slopes of rate-pitch functions did not differ significantly from the pure-tone references, suggesting their use for the encoding of within-channel fine frequency information via rate modulations in temporal fine structure stimulation strategies.

1. Introduction

Pitch is one of the most widely studied and passionately debated perceptual attributes in both acoustically and electrically evoked hearing. Theories on pitch perception have evolved from the earliest place (von Helmholtz, 1863) and temporal models (Wundt, 1880) to more refined spectral (Goldstein, 1973; Terhardt, 1979) and temporal autocorrelation (Licklider, 1959; Meddis and O'Mard, 1997) models, some combining place and temporal aspects (Wever, 1940; Wever and Bray, 1930), and to models based on spatial gradients of neural responses that are phase-locked to the traveling-wave induced basilar membrane motion (Loeb, 2005).

Abbreviations: CI, cochlear implant; RIB, research interface box; 2I-2AFC, two-interval two-alternative forced choice; pps, pulses per second; PSE, point of subjective equality; PTA, pure-tone average; SE, standard error of the mean

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In both acoustically and electrically evoked hearing, it has been shown that temporal rate and spectral place are two orthogonal dimensions of perception, with the first dimension being correlated to pitch, and the second dimension to what is commonly described as timbre (Plomp and Steeneken, 1971; Tong et al., 1983). While for acoustic stimuli temporal and place information covary, in electrically evoked hearing in cochlear implants (CIs) the two dimensions may be manipulated independently from each other. However, in many studies, also involving CI users, the two perceptual dimensions of pitch and timbre are not differentiated, primarily because subjects rarely can make a clear distinction between the two attributes. Thus, for simplicity, in the following the term 'pitch' will be used to describe sensations that allows listeners to order stimuli from 'low' to 'high', bearing in mind that both perceptual dimensions of pitch and timbre are likely to contribute to those sensations.

In normal-hearing listeners, Oxenham et al. (2004) investigated whether pitch perception is consistent with a purely temporal model or whether the place code is also an important component in the neural representation of periodic sounds. Pitch perception was compared between normal and 'transposed' acoustic stimuli, in which low-frequency temporal information was presented to high-frequency regions of the cochlea. This was accomplished by modulating a low-frequency half-wave rectified sinusoid on top of a high-frequency sinusoidal carrier. For all transposed stimuli, pitch perception was heavily compromised: frequency difference limens were significantly larger for transposed than for normal pure tones, F0 difference limens at 100 Hz for complex tones composed of harmonics 3–5 were unmeasurable in three of four subjects when the harmonics had been transposed, and the same complex tones could not be matched to pure tones at the fundamental frequency when they had transposed harmonics. The authors concluded that the tonotopic representation, i.e. the cochlear place where temporal information is presented, is crucial to complex pitch perception, suggesting that for periodic sounds temporal information ought to be presented at the right tonotopic place in order to elicit a salient pitch percept.

As more patients with residual hearing or unilateral hearing loss benefit from a CI, there are growing opportunities to compare pitch percepts elicited by electrical stimulation through the implant to pitch percepts elicited by acoustic stimuli in the same or contralateral ear. Such comparisons are relevant from both a practical point of view in terms of CI sound processor mapping and from a more fundamental point of view in terms of sound coding strategy design. In practical terms, an allocation of frequency bands in a multi-channel CI sound processor to electrodes in a way that the allocated spectral information closely matches the tonotopic electrode place might not only lead to a better acceptance of the CI sound, but also allow implant patients to reach asymptotic levels of speech perception faster after first implantation (Reiss et al., 2008). Recent studies on sound coding strategies have investigated possibilities to transmit temporal information in general, and low-frequency temporal fine structure in particular, more effectively through a CI (Müller et al., 2012; Riss et al., 2008; Schatzer et al., 2010). Temporal fine structure information may be crucial for the perception of speech in complex backgrounds (Qin and Oxenham, 2003) and tonal languages (Xu and Pfingst, 2003), as well as for the localization of sounds and perception of pitch (Smith et al., 2002). However, the results by Oxenham et al. (2004) suggest that the hypothesized benefits of representing additional temporal fine structure information might be limited unless that information is presented at the correct tonotopic place along the cochlea.

Several studies have investigated pitch percepts across acoustic and electric stimulation modalities in users of different cochlear implant systems (Baumann and Nobbe, 2006; Baumann et al., 2011; Blamey et al., 1996; Boëx et al., 2006; Carlyon et al., 2010b; Dorman et al., 2007; McDermott et al., 2009; Vermeire et al., 2008). Many of these studies found that the pitch elicited through stimulation of intracochlear electrodes was generally between one and two octaves below Greenwood's estimate (1961, 1990) for the frequency-place function in humans (Blamey et al., 1996; Boëx et al., 2006; Dorman et al., 2007). Blamey et al. (1996) conducted pitch-comparison experiments in 13 subjects with relatively poor hearing in their non-implanted ear. Results were quite variable across subjects, and the pitch elicited through stimulation of intracochlear electrodes was generally between Greenwood's prediction and three octaves below that prediction. Boëx et al. (2006), Baumann and Nobbe (2006), and Dorman et al. (2007) tested subjects that had better hearing thresholds in the non-implanted ear. Thus, pitch matching data were less compromised by hearing loss and abnormal cochlear function. When frequency-place maps were constructed, matches were in a range between Greenwood's prediction and two octaves below.

With the exception of one unilaterally deaf CI subject in Baumann et al. (2011), place-pitch matches in patients with normal or near-normal hearing in the non-implanted ear did not deviate consistently from Greenwood's prediction (Carlyon et al., 2010b; Vermeire et al., 2008). Vermeire et al. performed cross-modality pitch scaling experiments in 14 subjects with functional hearing in the non-implanted ear. They found that electrical stimulation produced a frequency-place function that, on average, resembles Greenwood's function, although results were also showing a large variability across subjects. In the study by Carlyon et al., four CI users with normal hearing in the non-implanted ear compared pitch percepts of electrical and acoustic stimuli presented to the two ears. Results of these comparisons did not show a deviation of electrical pitch percepts from the predictions of Greenwood's cochlear frequency-place equation. Another important observation in that report is that stimulus comparisons across electric and acoustic modalities are adversely affected by differences in perceptual quality, becoming highly susceptible to non-sensory biases. As a consequence, substantial range effects were encountered for all of the applied cross-modality comparison procedures. By carefully examining results for such range biases and discarding pitch matches that did not pass strict 'sanity' checks, Carlyon et al. found very little variability across subjects. While Carlyon et al. derived electrical place-pitch matches for electrode positions up to 360° from the round window, to our knowledge only the study by Vermeire et al. has obtained second-turn electrode matches from a larger number of subjects with near-normal contralateral hearing (however, without applying checks for non-sensory biases as in the experiment presented here).

In the present study, we conducted electric-acoustic pitch matching experiments in eight experienced MED-EL implant users having near-normal hearing in the non-implanted ear. All subjects were part of the larger group participating in the study by Vermeire et al. (2008). In the first experiment, frequency-place functions were determined for high-rate unmodulated trains of biphasic pulses presented in monopolar configuration on individual electrodes, including second-turn electrodes. In contrast to the pitch scaling procedure that was used in the 2008 study, in the present study we used an adaptive matching procedure and applied 'sanity' checks similar to those proposed by Carlyon et al. (2010b) in order to identify reliable pitch matches. As a result, we expected to find less variability in the frequency-place functions across subjects. Of interest was also the question whether frequency-place functions in our long-electrode subjects would show a systematic shift from the prior study, similar to other observations in short-electrode hybrid subjects (Reiss et al., 2007).