Comparisons of Pitch-Matching Methods to Predict Interaural Mismatch in Cochlear-Implant Users

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Introduction

Individuals with severe-to-profound hearing loss can regain access to sound through cochlear implantation. Many people with this type of hearing loss in both ears can opt to receive bilateral cochlear implants (CIs). Compared to individuals that have one CI and one deaf ear, individuals with bilateral CIs perform better in sound source localization and speech understanding in noise [1][2][3][4].

However, outcomes across patients with CIs are extremely variable due to several factors that vary from patient to patient [3][4]. One factor that leads to changes in sensitivity to binaural cues [5][6][7] and benefit listening to speech in noise [8] is interaural mismatch in place-of-stimulation (Fig. 1).

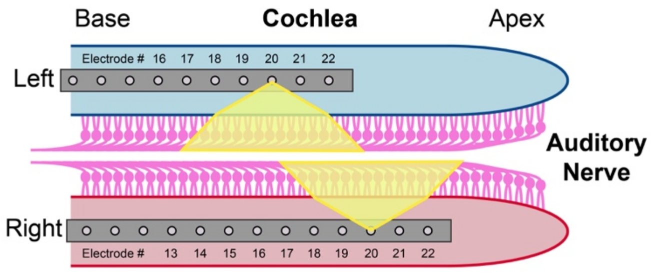

Fig 1: Spiral ganglion cell activation in both ears when electrode arrays are inserted with interaural mismatch in place-of-stimulation. The cochlea is presented as flat for ease of illustration. Yellow triangles represent spread of current from CI stimulation.

Due to limitations in CI surgery, it is not always possible to ensure that specific electrodes in each ear stimulate overlapping neural populations across the ears. After surgery, however, it may be possible to estimate electrodes that are matched interaurally in their places-of-stimulation. Thus, several psychophysical methods have been used by researchers to match interaural place-of-stimulation and stimulate electrodes with overlapping neural populations between the ears [9].

One such method is pitch-matching, which capitalizes on the fact that the perception of pitch changes depending upon place-of-stimulation, with more apical regions eliciting a perception of lower pitch [10]. Accordingly, this method assumes that when electrodes in either ear elicit the same pitch they are stimulating similar neural populations in each ear [9][11]. There are many ways to design pitch-matching procedures, with potential for some methods to be more accurate at the expense of additional testing time.

In order to make experiments using pitch-matching more efficient and clinically-relevant, it is desirable to determine whether different methods of pitch-matching yield similar results. If a faster and simpler method for testing pitch-matching yields similar results to a more time-intensive method, the former method should be used. The goal of this experiment was to determine whether two methods of pitch matching used in previous experiments by our laboratory yield similar estimates. It was predicted that pitch-matching methods would yield similar estimates.

Methods

Thirty-three patients with bilateral CIs participated in this study. They ranged in age from 19-85 with a mean of 55.5 years. Each patient had at least 6 months of experience with their CI in either ear before testing. Each CI had 22 electrodes with inter-electrode distances of 0.75 mm on average, though these distances vary depending upon device. Electrode number 1 was closer to the base (high frequency portion) of the cochlea and electrode number 22 was closer to the apex (low frequency portion) of the cochlea.

Cochlear implants were stimulated directly using Lara34 or RF GeneratorXS research processors provided by Cochlear, Ltd. These research processors allow experimenters to bypass clinical processors and avoid undesired changes to the signal delivered to CIs due to sound processing algorithms. Therefore, research processors allow experimenters a high level of control over the stimuli presented to the patient.

Stimuli were constant-amplitude, biphasic, monopolar pulse trains. Stimuli were presented at a rate of 100 pulses per second for a duration of 300 ms. Each pulse had a phase duration of 25-µs with an 8-µs phase gap. One subject was tested using a phase duration of 45-µs and 8-µs phase gap in the left ear, consistent with their clinical programming.

Before testing, a comfortable stimulation level was determined for each electrode. Level on each electrode was adjusted until loudness was balanced across all electrodes when presenting multiple electrodes within- and across-ears in a sequence. Each electrode was presented in a sequence at least once.

Two psychophysical procedures were used to estimate place-matched electrodes via pitch-matching as described in detail in a previous experiment [11]: (1) Direct pitch comparison (DPC) and (2) pitch magnitude estimation (PME).

DPC gives estimates of three pitch-matched electrodes in the right ear given three electrodes in the left ear. In contrast, PME gives global estimates of pitch across the entire electrode array in each ear. DPC and PME take 1.5-2 and 1 hour to complete, respectively, but it was thought that DPC is more accurate for the electrodes tested [11].

The DPC procedure was completed as follows:

1. Three electrodes were selected in the left ear at basal, middle, and apical regions of the cochlea.
2. Six comparison electrodes for each left-ear electrode (eighteen in total) were selected for the right ear.
3. Stimuli were presented sequentially across two intervals (in the left, then right ear) and ranked whether the pitch in the right ear was much lower (-2), lower (-1), same (0), higher (+1), or much higher (+2) than the pitch in the left ear. Stimuli could be repeated as many times as necessary.
4. Twenty repetitions were collected for each comparison electrode in the right ear, resulting in a total of 360 presentations.
5. The DPC estimate was determined by averaging responses across repetitions for each comparison electrode and choosing the electrode with the absolute minimum. If there was a tie, the electrode closer in number to the electrode in the left ear was chosen.

The PME procedure was completed as follows:

1. The eleven even-numbered electrodes were selected in each ear unless one was deactivated by the patient's audiologist in their clinical programming.
2. Patients were presented with a single interval of one electrode and rated the pitch between 0 (low) and 100 (high). The stimulus could be presented as many times as necessary.
3. Ten repetitions were collected for each electrode in the left and right ears, resulting in a total of 220 presentations.
4. The PME estimate was determined by taking the pitch-rating for the electrode in the left ear and finding the electrode with the same pitch-rating in the right ear.

To estimate the pitch-rating for each electrode with the PME procedure, data were fitted with a four-parameter logistic function (1).

$$y = A + \frac{B - A}{1 + \exp\{\frac{\alpha - x}{\beta}\}} \qquad (1)$$

where A is the upper-asymptote, B is the lower-asymptote, α is the mid-point along the x-axis, and β changes the slope.

Results

Example results using the DPC and PME procedure are shown for one subject in Fig. 2. Results from DPC (Fig. 2A) demonstrate monotonic increases in pitch perception with decreasing electrode number, suggesting that there is one electrode that corresponds to the most similar to the pitch elicited by the right ear. Most data were consistent with this pattern, but some patients exhibited non-monotonic changes in pitch across electrodes.

Results from PME (Fig. 2B) show a similar pattern to DPC in that perceived pitch increased as electrode number decreased. Data from PME demonstrate how the limits of perceived pitch can vary depending upon the ear. In the example in Fig. 2B, the right ear was perceived as higher in pitch at the apical- and basal-most electrodes. However, pitch elicited by stimulation of middle electrodes was similar between both ears.

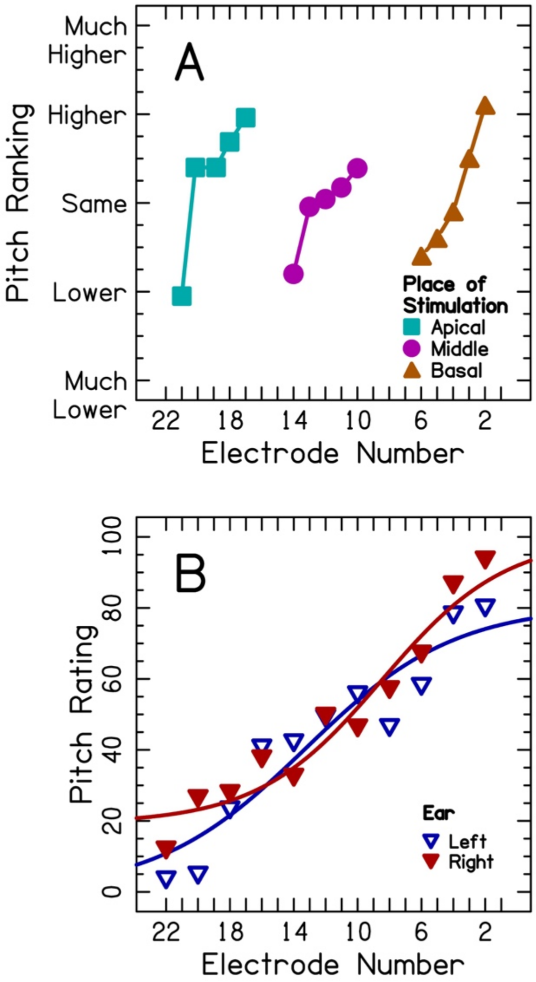

Fig 2: Example results from one subject in the A. DPC and B. PME pitch-matching tasks. The x-axis corresponds to the electrode presented, and is plotted in descending order to correspond to increasing pitch. A. The x-axis only corresponds to the right ear. The y-axis represents the mean pitch ranking across five repetitions. B. The y-axis represents the pitch rating (0 = low, 100 = high) of the electrode being presented. Data were fitted using Eqn. (1).

Pitch-matched electrodes were determined using the methods described for DPC and PME for each subject. The goal of this analysis was to relate the pitch-matched electrode using DPC and PME across subjects (Fig. 3). The results suggest that DPC and PME varied slightly, which is indicated by estimates that fell away from the line of unity.

First, systematic differences between estimates from DPC and PME were assessed. A mixed-effects analysis of variance (ANOVA) was computed with pitch-matched electrode estimate from the right ear as the dependent variable, method (DPC, PME) and region-of-stimulation (apical, middle, basal) as fixed effects, and participant as a random effect. Including a random effect for participant accounts for variability across individuals within the statistical analysis, and allows the results to be interpreted within-subjects. Unsurprisingly, the results of the ANOVA indicated that estimates varied by region-of-stimulation, with more apical places-of-stimulation in the left ear being pitch-matched with more apical places-of-stimulation in the right ear [F(2,175)=281.11, p<.0001]. There was no significant difference between DPC and PME estimates [F(1,175)=0.45, p>.10]. There was also no interaction between region-of-stimulation and pitch-matching method [F(2,175)=0.29, p>.10].

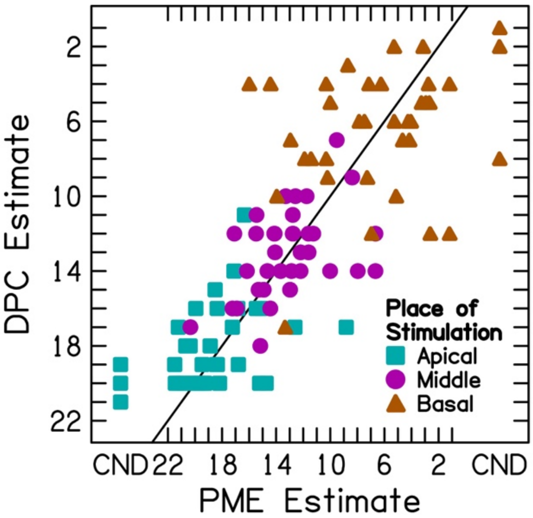

Fig 3: Pitch-matched electrodes in the right ear using DPC and PME. The x- and y-axes represent the pitch-matched electrode in the right ear using the PME and DPC procedures, respectively. The black line shows the line of unity, i.e., how results would have appeared if estimates from each method were identical. Estimates that could not be determined because they fell outside of the existing 22 electrodes were designated with Could Not Determine (CND).

Second, the predictive value of PME estimates on DPC estimates was determined. Pitch-matched DPC estimates were fit with a linear regression with PME estimates as a predictor and the intercept was allowed to vary by subject to account for differences between subjects [12]. Data were excluded from analyses where PME estimates could not be determined. The results indicated that PME estimates were a significant linear predictor of DPC estimates [t(33)=13.125, p<.0001]. The regression coefficient had a 95% confidence interval of 0.85 ± 0.13. Thus, the confidence interval implies that the regression slope was below 1. Overall, the regression predicted 64% of the variance in DPC estimates [adj. $R^2 = 0.64$].

A slope below 1 suggests that DPC estimates occurred over a smaller range than PME estimates. This prediction was tested by using Bartlett's test of heterogeneity of variances for each region-of-stimulation (basal, middle, and apical) using Bonferroni corrections for multiple comparisons. The results indicated that there was no significant difference in the variances between DPC and PME for basal [$K^2(1)$=4.25, p>.05] and middle [$K^2(1)$=2.15, p>.05] electrodes. However, there was a significant difference in variance between DPC and PME for apical electrodes [$K^2(1)$=9.17, p<.05].

Discussion

This experiment examined whether two methods of interaural pitch-matching yielded similar results. Two different methods of pitch-matching, DPC and PME, were used with three reference electrodes in the left ear. Overall, results from PME and DPC were similar, with no significant difference between methods and a high correlation coefficient in the regression between DPC and PME estimates. This result implies that both procedures might be effective ways to determine pitch-matched electrodes.

While there was no systematic difference in the estimates of pitch-matched electrodes between methods, the slope of the regression predicting DPC estimates from PME estimates was below 1. This suggests that DPC estimates varied over a smaller range than PME estimates (Fig. 3), which was confirmed for apical electrodes. The significance of this difference in variability is not immediately obvious. On one hand, if the variability is unrelated to changes in pitch and is simply due to the way that the task is designed, then PME would be a poor choice for pitch-matching in future experiments. However, it is also possible that greater variability with PME estimates are reflective of actual pitch changes experienced by the patient, and that DPC results in a smaller amount of variability because of task-related problems.

With respect to DPC, it has been demonstrated recently that pitch-matching estimates in listeners with bilateral CIs and single-sided deafness are highly-dependent upon the range of frequencies or electrodes tested [13][14]. Participants in these studies tend to indicate that the electrode in the middle of the tested range corresponds to the same pitch as the contralateral electrode. It is possible that participants in the present study used a similar listening strategy, and it is difficult to determine how this affects the interpretability of results. Therefore, one issue with DPC in general is that experimenters inherently bias testing by choosing the electrode range to be tested.

If listeners begin to adjust to the range of pitches being tested in an experiment, then one intuitive solution would be to use pitch-matching methods that test over a large range of possible places-of-stimulation that occur during real world listening. The primary strength of PME is that it tests over the entire range of electrodes. If listeners begin to adjust their responses toward the middle of the tested range, the results should exhibit relative differences in pitch between electrodes in either ear.

One additional benefit of PME compared to DPC is that testing occurs over a shorter duration, a pitch-matched electrode in the right ear could be estimated for any virtually any choice of electrode in the left ear. To estimate the pitch-matched electrode for electrodes not tested in the left ear in DPC the experimenter has to make assumptions about the amount of shift in interaural place-of-stimulation for other electrodes. In contrast, because PME is tested over the entire array, no such assumptions are necessary. Instead, estimates can be made from the fitted curve.

There are several limitations to PME as well. Fig. 2B shows regions for which fitted curves in the left and right ear do not overlap. If a pitch-matched electrode is desired for electrodes at the far ends of the arrays, towards the apex or base, then it may not be possible to determine estimates within the 22 electrodes in a CI electrode array (CND in Fig. 3). However, most of the estimates that fell outside of the range of real electrodes were reasonably near (2-3 electrodes outside of the actual range). It is possible that the electrode in the left ear did not have a corresponding electrode in the right ear that stimulated overlapping or surviving neural populations. Then the closest electrode would be the apical- or basal-most electrode in the right ear. This is roughly consistent with what was observed in the data (Fig. 3).

Finally, it has been demonstrated that the perceptual mapping of pitch to place-of-stimulation changes over time in patients with CIs [15]. Studies concerning changes in pitch perception over time suggest that the place-of-stimulation to pitch map for a specific patient eventually converges with experience. These studies propose that plasticity in perception might be necessary after CI surgery to adjust to differences in the frequency to place-of-stimulation map with normal hearing. It may be that pitch perception is highly susceptible to task-related effects, and that experimenters should be careful before using a particular task involving pitch perception.

In summary, DPC and PME yielded similar predictions for pitch-matched electrodes in the right ear. Recent evidence increasingly suggests that the outcomes of DPC might be dependent upon the range of electrodes chosen by experimenters [13][14]. Additionally, PME is completed using a wide range of electrodes in each ear, providing a global estimate of pitch matches across the array. The results of these analyses suggest that pitch-matching using PME may be the ideal approach since it is also faster to complete.

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