Psychoacoustic abilities of CI users in relation to speech understanding and localization in a reverberant room

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Introduction

Over recent years we tested speech understanding and localization abilities of bilateral CI users with an extensive test battery [1, 2]. Figure 1, top panel, shows results of the speech test for seven bilateral CI users. Speech reception thresholds (SRTs) with speech and noise presented from the front were measured in the free-field. SRTs were between 0 and +6 dB, i.e. performance differed despite all participants using the same cochlear implant (CI) devices.

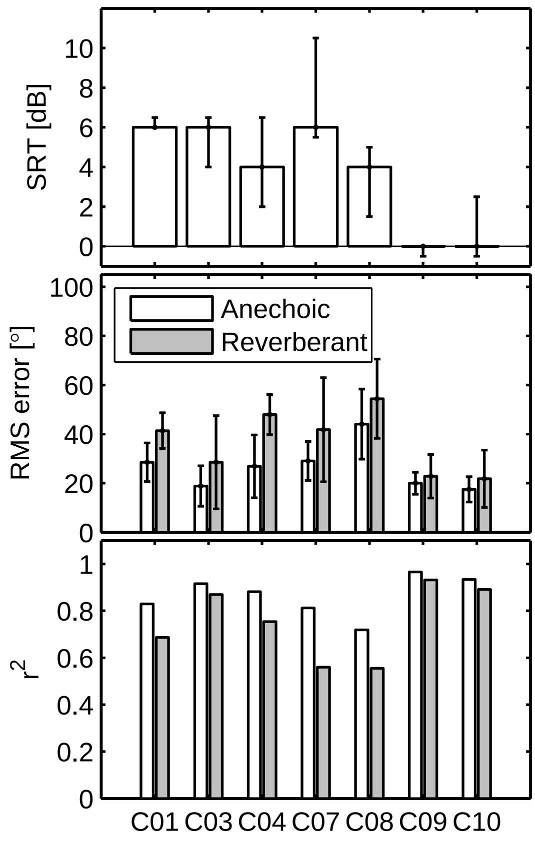

Figure 1: Speech reception thresholds (top panel) and localization performance (bottom two panels) for seven bilateral CI users.

In addition to speech understanding, localization performance in an anechoic and a simulated reverberant room was investigated. Figure 1, mid and bottom panel, shows root-mean-square (RMS) localization errors and coefficients of determination r^2. Focusing on the white bars, i.e. localization performance in the anechoic room, we again observed a substantial difference in performance between participants. While the best performers (C09 and C10) showed localization errors around 20°, the worst performers showed RMS errors two to three times larger. A similar picture was observed for r^2, a measure to estimate the linearity between target direction and perceived direction. A magnitude of 1.0 would denote perfect linearity. Again, only C09 and C10 came close to this optimum. Most other CI users were well below 0.9.

Similar localization tests were conducted in a moderately reverberant room (Figure 1, mid and bottom panels, grey bars). Reverberation was characterized by the direct-to-reverberant ratio, which in our case was at –3 dB. Both measures for localization performance worsened when the reverberation was introduced, an effect that proved significant (Wilcoxon signed-rank test, one-sided, $p < 0.01$).

Large performance differences across cochlear implant participants are frequently reported. However, given that participants in our study used similar devices and were well satisfied with their CIs the differences are somehow surprising. Performance differences may thus be related to differences in basic psychoacoustic performance. To investigate this we re-invited the participants and took basic psychoacoustic performance measures using direct stimulation of the implants to relate them to participant's abilities in the free-field tests. Namely, we measured binaural sensitivity and forward masking in order to predict r^2 and SRTs from basic psychoacoustic measures.

Methods

Participants

Seven bilateral CI users, aged 30 to 78 years, took part in this study. All were users of devices manufactured by Cochlear Ltd. With the exception of C09 they were implanted sequentially. Their hearing loss was due to different etiologies (detailed information is given in [1], where the numbering of participants corresponds with the numbering in this paper).

General procedure

We used direct stimulation hardware supplied by Cochlear Europe Ltd. Two modified L34 speech processors were directly controlled via Matlab to generate the stimuli. Biphasic, negative leading, current pulses were delivered in monopolar mode with both reference electrodes as return electrodes (MP1 and MP2 mode). In all experiments the pulse rate was fixed at 900 pps. Before we measured basic psychoacoustic performance we tested electrode impedances, measured C- and T-levels and balanced the loudness of the stimuli across all electrodes on both ears. In addition, for each participant we selected three binaurally matching electrode pairs in the basal, mid and apical region of both cochleas for the binaural sensitivity tests.

Binaural sensitivity tests

In these tests we estimated binaural sensitivity from lateralization data. We hypothesized that better sensitivity to interaural cues would correspond with better localization abilities in the free-field.

Stimuli were interaurally displaced (lateralized) by either interaural level differences (ILDs) or interaural time differences (ITDs) in the signal envelopes. Participants judged the lateral displacement by steering a marker on a horizontal straight line. They were instructed to think of this line as the intracranial connection of their ears and had thus endpoints marked with labels “left-ear” and “right ear”.

Lateralization based on ILDs was done using ongoing pulsetrains with slow on- and offset slopes. Stimuli were additionally level-roved to reduce possible monaural lateralization cues. Nominal ILDs were between –16 and 16 Cochlear current units (CUs).

Lateralization based on envelope ITDs was investigated with a stimulus consisting of six short (10 ms) pulses interrupted by 120 ms of silence. These stimuli provided strong envelope modulation and should thus be easy to localize based on envelope ITDs. Nominal ITDs were in between -1.6 and 1.6 ms.

Lateralization data were analyzed and sensitivity measures were calculated according to [1]. This was done for each participant and each electrode pair in isolation. Therefore a line was fit to the lateralization data using a least squares error minimization. Then the mean standard deviation of the lateralization data was calculated and divided by the steepness of the line. The resulting value gives an estimate of sensitivity such that two similar stimuli differing only by this sensitivity value could be distinguished in 69.1% of trials.

Forward masking test

Forward masking was measured using a standard paradigm. A short 10 ms probe followed a 300 ms long masker after a short delay. Masking was characterized by the level of the probe necessary to remain just audible. This was measured using an adaptive tracker. The whole measurement was done on a single electrode on the participant’s better ear with the masker level fixed at 70% of the electro-dynamic range of the electrode. Our hypothesis was that a quicker decay of forward masking would correspond with greater perceptual separation between direct sound and reverberation in the localization task in the reverberant room. Thus we would expect better localization performance for participants with quicker decay. In addition, quicker decay should also help to preserve modulation perception of the speech stimuli and should thus help speech understanding in noise.

Decay of forward masking was characterized such that a line was fitted to the forward masking data when printed as a function of target-delay. The fit was done using a least square error minimization. Decay was then set equal to the steepness of the line.

Results

Basic psychoacoustic performance measures

Table 1 gives basic performance estimates for the sensitivity to ILDs (“D_{ILD}”), envelope ITDs (“D_{ITD}”) and forward masking decay (“SL”). Note that for the binaural sensitivity measures only best performance across the three electrode pairs is given.

Participant	Psychoacoustic performance		
	D_{ILD} [CU]	D_{ITD} [µs]	SL
C01	5	3008	-13.2
C03	5	1733	-26.8
C04	4	867	-25.8
C07	6	6402	-38.2
C08	26	3553	-23.5
C09	10	256	-25.9
C10	4	280	-22.7

Table 1: Performance in the direct stimulation tests. D_{ILD}: best sensitivity to ILDs; D_{ITD}: best sensitivity to envelope ITDs; SL: slope of the forward masking data.

All participants were able to lateralize based on superimposed ILDs. Correlations between nominal ILDs and lateralization data were significant for all tested electrode pairs. Sensitivity was in between 4 CU and 26 CU. Envelope ITDs were less efficient as a lateralization cue. The sensitivity to ITDs was between 256 and 6402 µs and thus often outside the physiologically useful range which is below 700 µs. In addition, the correlation between nominal ITDs and lateralization percept remained non-significant in many cases.

Relation of basic psychoacoustic measures to free-field localization and SRTs

In a further step we wanted to know how the basic psychoacoustic measures relate to the localization and SRT data collected in free-field. To examine this we used a multiple linear regression with the basic performance measures as the independent variables. The dependent variable was either r^2 in the localization experiments or SRTs of the speech test. We then calculated b-weights for each independent variable. A higher b-weight indicates that the corresponding factor contributes more to the linear regression, i.e. is more important for the prediction of the dependent variable.

Figure 2, top panel shows the regression results for the SRT data. Overall, the quality of the regression was poor denoted by an R^2 of 0.58 only. Thus the three basic psychoacoustic measures only explained 58% of the variance in the data. The largest weight (1.19) was associated with sensitivity to ITDs. However, this should not be attributed to a causal dependency between ITD sensitivity and SRT because the former is a binaural measure while speech perception was measured in a strictly monaural task. We assume that a common underlying factor like, e.g., better nerve survival or better spectral resolution, triggered this strong dependency.

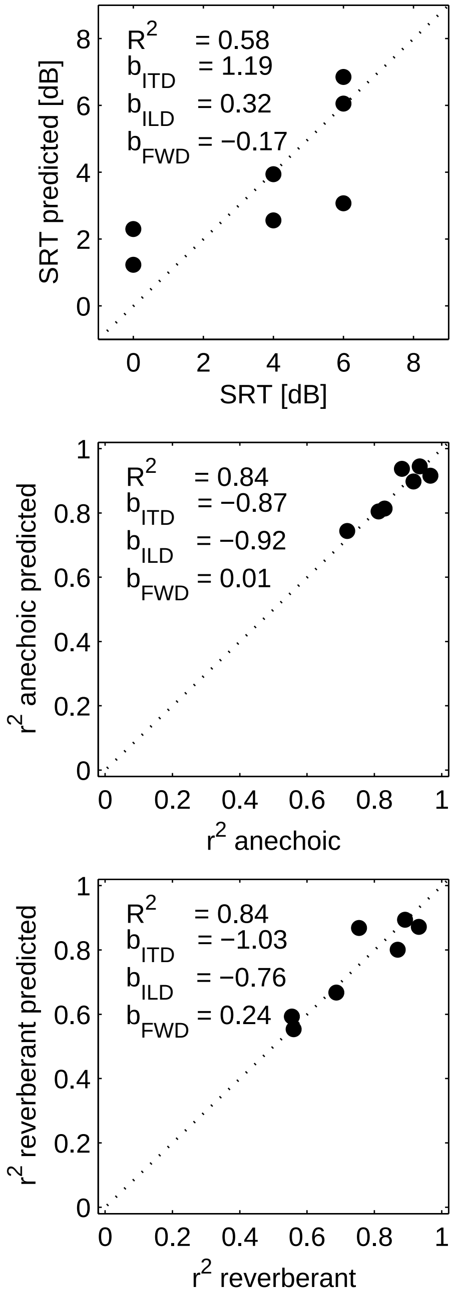

Figure 2: Multiple linear regression to predict SRT (top panel) and r^2 for localization in anechoic and reverberant conditions (mid and bottom panel respectively). Inlays give the overall quality of the regression (R^2) and the weights associated with the obtained basic psychoacoustic performance measures.

The mid panel in Figure 2 shows the prediction for r^2 measured in the anechoic room. Overall the three basic psychoacoustic factors explained 84% of the variance. The linear regression on the localization data is thus considerably better than the regression on SRTs.

The largest weight was associated with the sensitivity to ILDs, followed by sensitivity to envelope ITDs. This is in line with previous studies ([3, 4]), who find that bilateral CI users mainly localize based on the ILD cue. ITDs also played a large role in the regression but were less important than ILDs. Forward masking slopes only marginally influenced the outcome of the regression.

The importance of the basic psychoacoustic measures changed when r^2 was analysed for the localization task in the reverberant room (Figure 2, bottom panel). The overall quality of the regression remained high: Again, 84% of the variance was explained by the basic psychoacoustic factors. However, for localization in reverberant space the largest weight was associated with the sensitivity to envelope ITDs. Nevertheless, contribution of ILD sensitivity remained strong. Forward masking slopes again only played a minor role. We thus conclude that sensitivity to envelope ITDs was relatively more important to maintain localization ability in reverberation.

Discussion

We measured sensitivity to binaural cues and forward masking using direct stimulation of cochlear implants and related the results to localization performance in anechoic and reverberant conditions as well as speech understanding in noise obtained with the patient's own speech processor. Localization performance in anechoic conditions was best predicted by the sensitivity to ILDs. Speech understanding in noise and localization in a reverberant room was best predicted by sensitivity to envelope ITDs. However, because speech reception thresholds were measured in a purely monaural task there should be no underlying causal dependency for the relation of SRTs to binaural ITDs.

The notion that bilateral cochlear implant users localize based on ILDs in anechoic conditions is well known (e.g. [3, 4]). However, this study adds that for localization in reverberant rooms bilateral CI users maintain localization performance best when they show high sensitivity to envelope ITDs. Presumably these participants are able to exploit binaural information in signal onsets which are less corrupted by room reverberation. Similar mechanisms have been described for normal-hearing listeners (e.g. [5]).

Signal processing in current cochlear implants encodes envelope ITDs with some accuracy. Our study shows that not all CI users are able to use envelope ITDs. Therefore an open question is how sensitivity to envelope ITDs can be restored for those CI users who lack it. One possibility would be to provide training. Rowan and Lutman ([6]) showed that training can improve discrimination of envelope ITDs. However, their study was done with normal hearing participants using stimuli imitating those encountered in CIs.

How their result would translate to CI users is, to our knowledge, unknown. In addition, it is unclear if better discrimination of envelope ITDs would also result in better localization in a reverberant room.

Another possibility is to improve CI processing to better transmit envelope ITDs by enhancing signal onsets. A method for this was developed by Seeber and Monaghan ([7]) and presented in a companion paper. In a vocoder study with normal-hearing listeners they were able to show that their method improved envelope ITD discrimination and lateralization performance while maintaining speech understanding. Evaluation of this algorithm with actual CI users is underway.

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