Binaural-bimodal stimulation degrades neural coding of interaural time differences

Introduction
Unilateral cochlear implants (CIs) allow the functional restoration of binaural hearing in subjects with single-sided deafness (SSD). However, speech perception in noise and directional hearing in SSD-CI users is typically poorer than in normal hearing listeners, indicating suboptimal binaural integration of unilateral CI stimulation and contralateral acoustic stimulation. In order to characterize the limitations in the neural representation of binaural cues in bimodal (combined electric/ acoustic) stimulation, we quantitatively compared phenomenological aspects (tuning curves) and functional efficacy (Fisher information) of interaural time difference (ITD) coding of single neurons in the inferior colliculus in response to unimodal (bilateral acoustic) and bimodal stimulation. Temporal offsets between unimodal and bimodal tuning curves were adjusted to test the effects of acoustic and electric processing delay mismatches on coding efficacy to bimodal ITDs.

Methods

IMPLANTATION
- Normal hearing adult gerbils (N=22)
- Round window implantation

STIMULATION
- Low rate stimulation (7-40 Hz; Fig. 1):
  - Acoustic pulses (100 µs)
  - Electric biphasic pulses (80 µs/µs)

RECORDING
- Ketamin/Xylazine anesthesia
- Single neurons in inferior colliculus
- ITD range typically +/-2000 µs in 50-200 µs steps

ANALYSIS
- ITD sensitivity (signal-to-total variance ratio, STVR). Neural responses were defined ITD sensitive if the ITD dependent variance was significantly greater than the total variance (F test, P=0.025 Hancock et al., 2013).
- ITD tuning metrics: ITD at maximum slope (ITDms); ITD at maximum spike rate (ITDbest); tuning halfwidth (HW) at half peak response (Fig. 2).
- Neural ITD discrimination thresholds (NDT; standard deviation based on signal detection theory; Sekitani 1973) re ITDms for D=10.
- Fisher information (accuracy of ITD estimation, calculated from spike rate):

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 f(\text{ITD}) = \frac{\text{f(\text{ITD})}^2}{\text{Var(\text{ITD})}}
\]

where f(\text{ITD}) denotes the slope of the rate-ITD function and Var(\text{ITD}) the variance of the spike rate across all ITDs.

Results

Fig. 3. Rate-ITD functions in response to unimodal acoustic (black) and to bimodal stimulation (red) can have similar shapes (A-D). Raw spike rates and best fits are shown in each panel. Differences in response strength (C: green arrow) and temporal offsets (D) between responses to unimodal acoustic and bimodal ITDs are indicated (green arrows).

Fig. 4. STVRs to unimodal and bimodal stimulation in the same neurons were significantly correlated (A: solid line: linear regression), and STVRs to unimodal ITDs were significantly higher than those to bimodal ITDs (B: Wilcoxon Signed Rank, P=0.024).

Fig. 5. Maximal Fisher information for responses to unimodal acoustic and to bimodal ITDs were significant correlated (A). Fisher information to unimodal ITDs was significantly higher than to bimodal ITDs (B: Wilcoxon Signed Rank, **P<0.001).

Fig. 6. Delays were adjusted to match ITDms (A: green arrow) and ITD best (B) between unimodal and bimodal rate-ITD functions. Over a wide range of central ITDs, averaged Fisher information to unimodal ITDs (black) was higher than that to bimodal ITDs (red). At maximum average (color-coded circles in C), this difference in Fisher information reached significance (D: Wilcoxon Signed Rank, **P<0.001). Delay adjustments (green) significantly increased Fisher information to bimodal ITDs (C, D: Kruskal-Wallis on Ranks, **P<0.01, ***P<0.001), but Fisher information to bimodal ITDs remained below that to unimodal ITDs.

Conclusions
- Bimodal stimulation reduces tuning acuity and degrades information density of neural ITD coding.
- Balancing the time delay between the two stimulation modes partially restores the efficacy of bimodal ITD coding.
- Nevertheless, bimodal ITD coding remained less accurate when compared to the natural unimodal condition.
- Additional strategies for enhancing the discrimination of bimodal ITDs need to be identified.

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