Model-based Analysis of ITD Perception in Normal & Hearing Impaired Listeners

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Introduction

- Sensorineural hearing impaired (HI) listeners often face difficulties localizing sound sources and have poorer than normal interaural time differences (ITDs) sensitivity, possibly due to deficits in their coding.
- It has been suggested that ITDs are processed by specialized cells in the brainstem known as coincidence detectors, which receive input from the auditory nerve (AN) from both ears.
- However, how cochlear impairment affects the coincidence detectors remains to be investigated.
- We developed a model capable of predicting just noticeable differences (JNDs) of ITDs in normal hearing (NH) and HI listeners based on simulated responses of the AN. We evaluated the model's performance by comparing its output with ITD sensitivity results from literature.

Materials & Methods

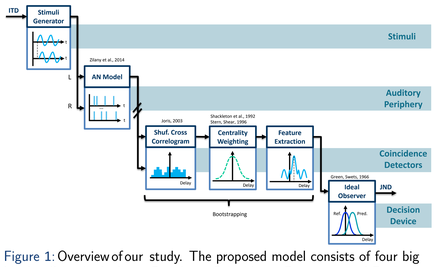


Figure 1: Overview of our study. The proposed model consists of four big blocks: Stimuli, Auditory Periphery, Coincidence Detectors, and Decision Device.

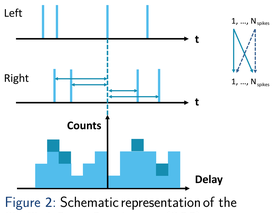


Figure 2: Schematic representation of the Shuffled Cross Correlogram (SCC) computation.

Binaural Stimuli

- **NH**: pure tones with frequency $f = \{250, 500, 750, 1000, 1250, 1500\}$ Hz, 70 dB SPL; bandpass noise centered at $f_c = \{500, 4000\}$ Hz with bandwidth $bw = \{100|115, 270|500|919\}$ Hz, 35|80 dB SPL (reported by Smoski and Trahiotis, 1986; Gabriel et al., 1992; Hawkins and Wightman, 1980). **HI**: bandpass noise with same characteristics as in the NH case, 80|85 dB SPL.
- Duration = 500 ms (including sinusoidal 20 ms onset and offset ramps).
- Reference condition with ITD = 0 μs. Experimental conditions with imposed ITDs of $\{10, 20, 40, 80, 160, 320, 640\}$ μs (right channel delayed).

Periphery

- Auditory periphery model (from eardrum to AN) proposed by Zilany et al. (2014).
- Simulation of the spike trains output by a neuron (tuned to the stimulus f/f_c) performed 270 times.
- Model allows tuning inner/outer hair cell (IHC/OHC) level of impairment (in a 1:2 proportion) using audiogram information.

Coincidence Detectors

- The Shuffled Cross Correlogram (SCC) analysis proposed by Joris (2003) was used to compare the spike trains of the left and right ears (Fig. 2).
- The central portion of the SCC was enhanced using the weighting functions proposed by Shackleton et al. (1992) or Stern and Shear (1996) to account for small ITD values being weighted more strongly and to avoid ambiguity in the ITD estimation.
- The predicted ITD was defined as the time delay of the maximum peak of the enhanced SCC.
- ITD prediction distributions were obtained by bootstrapping 20 % of the spike trains 100 times.

Decision Device

- Reference/experimental ITD distributions were fed to a receiver-operating characteristic (ROC) analysis (Green and Swets, 1966).
- The ROC area under the curve was plotted as a function of the imposed ITD.
- The neurometric curve was obtained by fitting the sigmoid function $AUC = a + \frac{b-a}{1+10^{(c-ITD)\cdot d}}$.
- We defined the ITD JND at 75 % of the neurometric curve (Brughera et al. 2013, 79.4 %; Smoski and Trahiotis 1986; Gabriel et al. 1992; Hawkins and Wightman 1980, 75 %).

Model Output

(Enhanced) SCC functions as a binaural coincidence detector

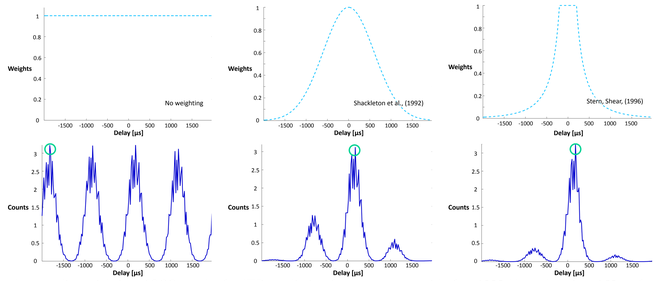
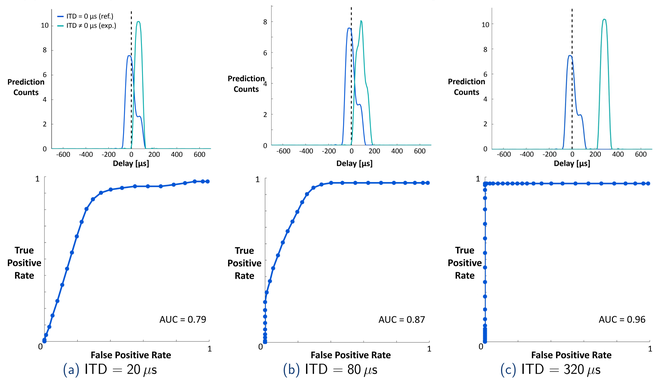


Figure 3: Example centrality weighting of SCCs used for ITD prediction for a pure tone with $f = 1000$ Hz and ITD $= 160$ μs for a NH listener.

Bootstrapped ITD prediction distributions allow ROC analysis



(a) ITD $= 20$ μs (b) ITD $= 80$ μs (c) ITD $= 320$ μs

Figure 4: Example ITD prediction distributions and their corresponding ROC curves for a pure tone ($f = 500$ Hz) using the Stern and Shear (1996) weighting for a NH listener.

ITD JNDs are computed from the 75 % point of the neurometric function

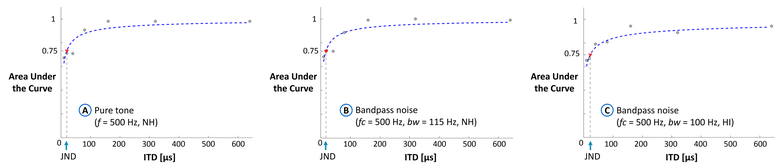


Figure 5: Example neurometric functions using the Stern and Shear (1996) weighting.

Comparison vs Behavioural Data

ITD JND trends can be predicted by the model for NH and HI listeners

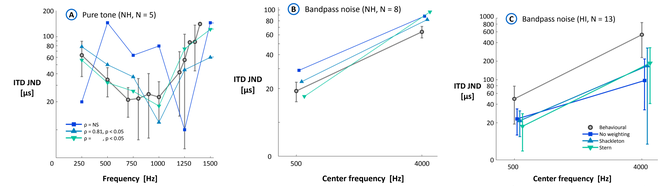


Figure 6: Comparison between behavioural data and model predictions. **A**: Data from Brughera et al. (2013). **B**: Data from Smoski and Trahiotis (1986) and Hawkins and Wightman (1980). **C**: Data from same studies as in B plus study from Gabriel et al. (1992). In B and C, the *bw* used for each f_c corresponds to the one used in the respective studies.

Modelled ITD JNDs of HI listeners are correlated with behavioural data but underestimated

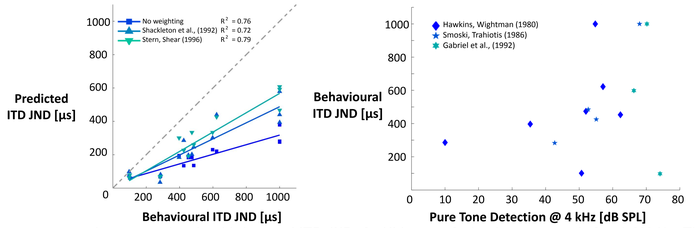


Figure 7: Direct comparison between predicted and behavioural ITD JNDs for HI listeners for bandpass noise with $f_c = 4,000$ Hz. The model underestimates behavioural ITD JNDs, although results show significant R^2 values ($p < 0.01$). This could be explained by the non-significant correlation between the participants' behavioural data and their auditory thresholds.

Discussion

- The SCC reflects activity of neural coincidence detectors across different delay values.
- Centrality weighting allows for better ITD JND predictions, specially for stimuli with periodic SCC.
- Stimuli with high frequencies show larger differences compared to behavioural data. This could be explained by the inability of the SCC (in its current form) to capture envelope and temporal fine structure separately.
- The model represents a best case scenario where it only considers peripheral hearing impairment, although there are additional factors that may affect the binaural perception of HI listeners (e.g., age, cognitive, etc.).
- The predictions are in line with data trends, allowing the model to be used to investigate the factors underlying the large variability observed across participants.

Conclusions

In this work, we presented a computational model capable of predicting trends for ITD JNDs for pure tones and bandpass noise for NH and HI listeners. These results provide a basis for a model-based quantification of ITD coding at the auditory periphery level. Future work will be focused on using the current approach to predict ITD discrimination performance in listeners with acoustic and electric hearing and to optimize hearing aids/cochlear implants signal processing.

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