A Computational Model for Sensitivity to Fast Frequency Chirps in the Inferior Colliculus

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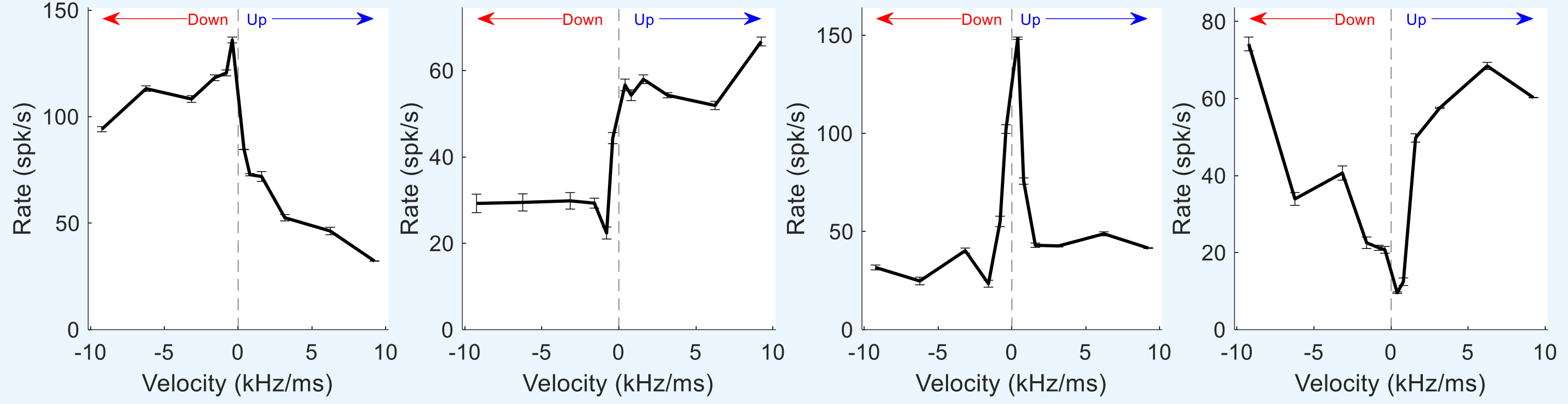
Introduction

- Mammalian inferior colliculus (IC) neurons show remarkable sensitivity to direction and velocity of periodic, fast, frequency sweeps (chirps) (Steenken et al., 2022)
- Chirp-velocity tuning can be described by a rate-velocity function (RVF), based on responses to single chirps

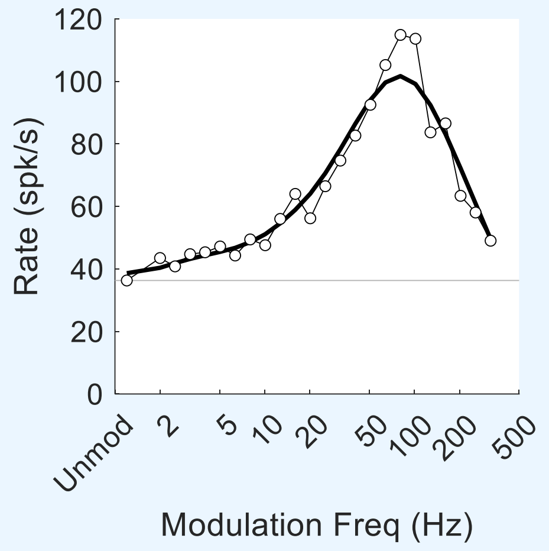
Four Example IC RVFs



- A possible source for IC direction/velocity tuning arises in octopus cells of the posteroventral cochlear nucleus (PVCN) (Lu et al., 2022), which inhibit the IC via the ventral nucleus of the lateral lemniscus (VNLL) (Adams, 1979).
- Here, we demonstrate that delayed inhibition with direction sensitivity yields an IC model cell with physiologically plausible RVFs and modulation transfer functions (MTFs, Joris et al., 2004).

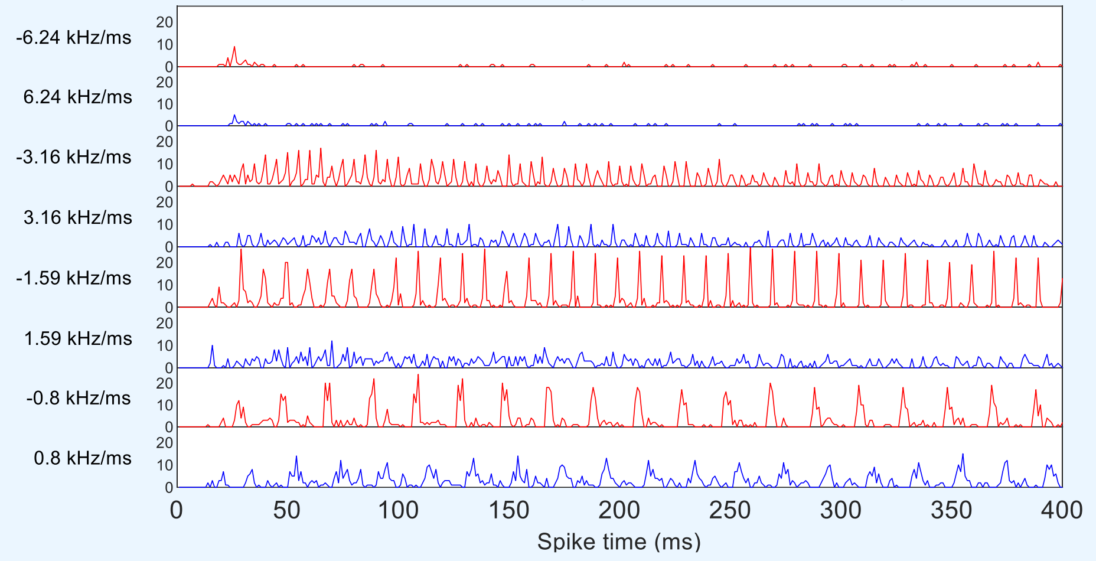
MTF (Data)

Band-enhanced (BE) MTF



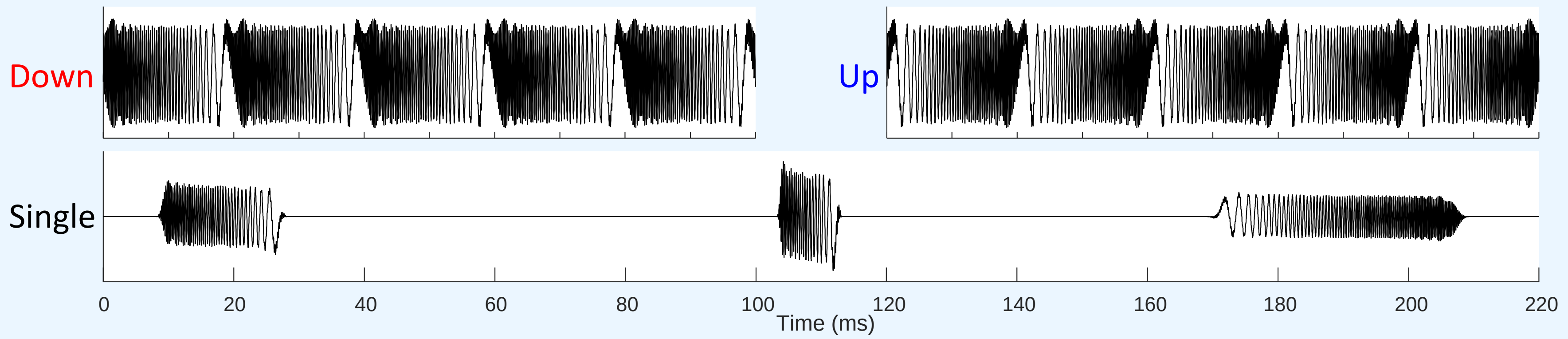
Schroeder PSTH (Data)

Note differences in rate for responses to downward (red) vs. upward (blue) sweeps



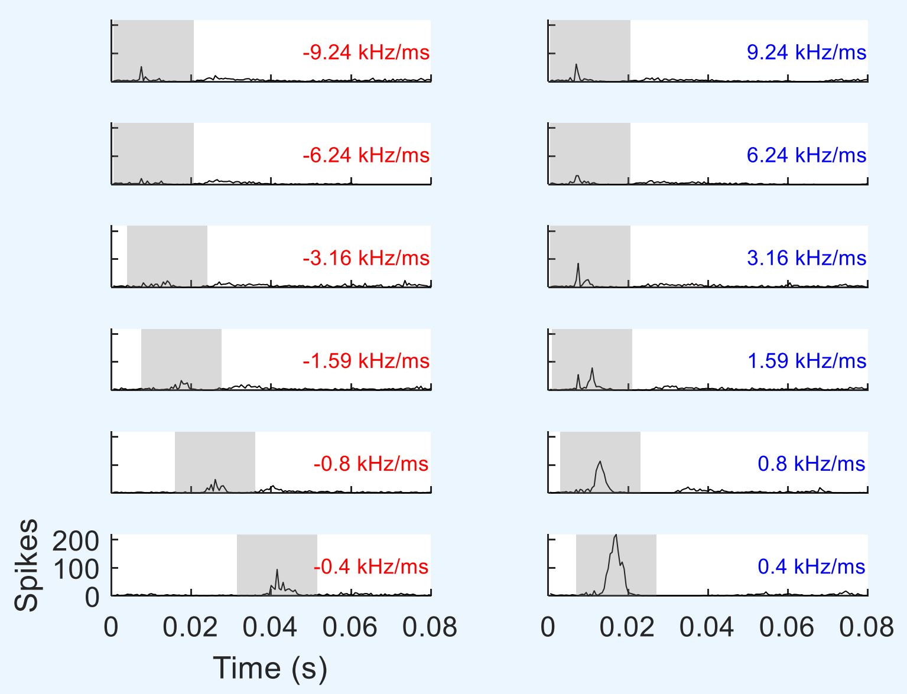
Methods - Stimuli and Analyses

- Chirp stimuli were derived from the Schroeder-phase harmonic complex, which has a phase function that results in a linear frequency sweep from the fundamental frequency (F0) to the highest harmonic (here, 16 kHz) within each fundamental period.

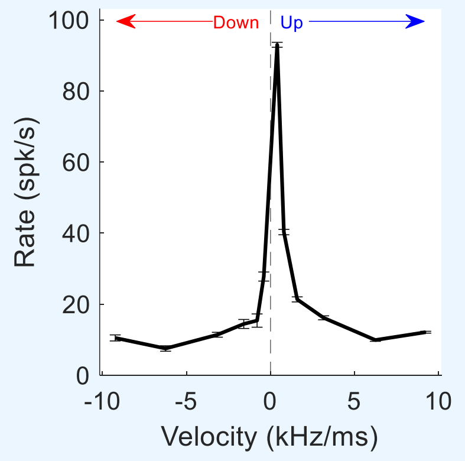


- Single Schroeder-chirps had varying velocity (0.40, 0.80, 1.59, 3.16, 6.24, and 9.24 kHz/ms) and direction (downward and upward)
- RVFs show average rate over a 20-ms window centered around the PSTH peak, versus velocity
- MTFs were generated using 1-s wideband (0.1–10 kHz) sinusoidally amplitude modulated noise, with modulation frequencies ranging from 2 – 350 Hz.

Chirp PSTH (Data)

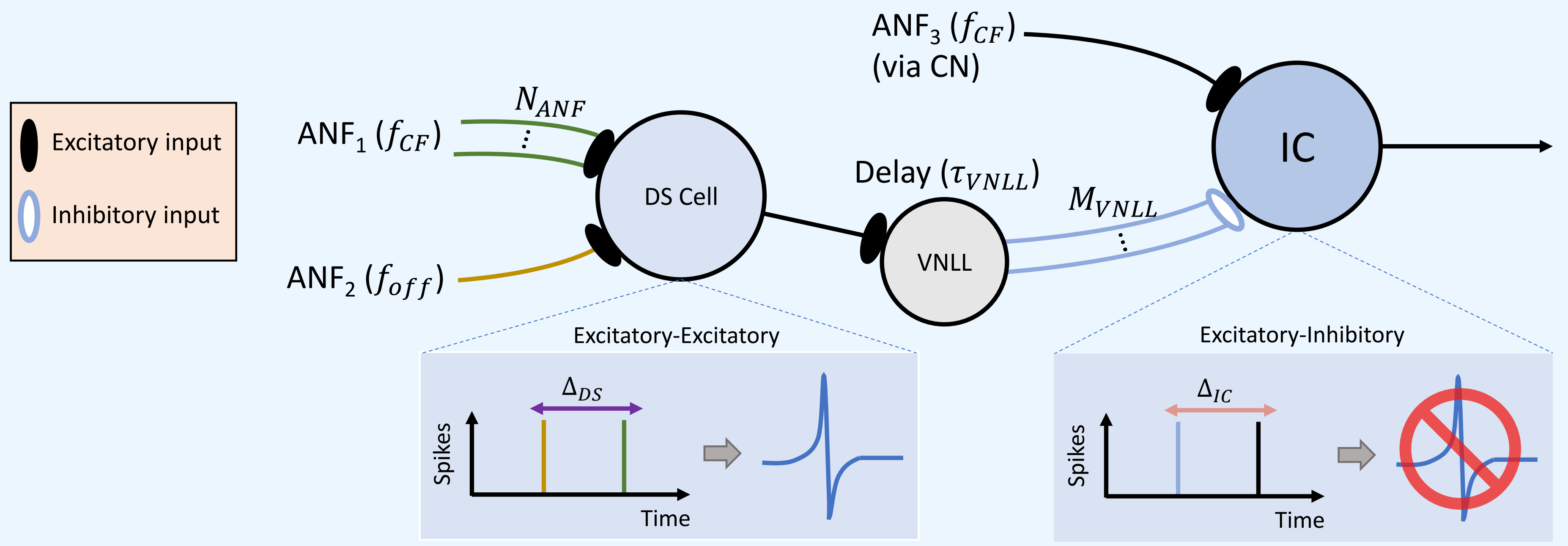


RVF (Data)



Methods - Modeling

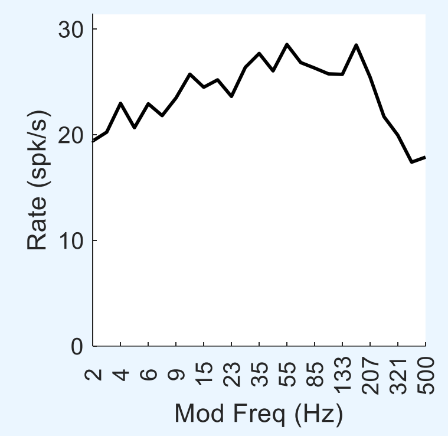
- Auditory-nerve-fiber (ANF) inputs were instantaneous rates, generated using Zilany et al. (2014).
- A simple direction-sensitive (DS) cell had two excitatory ANF inputs, one on- and one off-characteristic frequency (CF). The neuron fired when both inputs arrived within a time window (Δ_{DS}) (Krips and Furst, 2009).
- The IC model received one excitatory AVCN input at CF and was inhibited by the DS cell input with delay (τ_{VNLL}). Inhibition reduced the probability of firing for a time window (Δ_{IC}) following inhibition.
- Excitatory and inhibitory strengths were controlled by the number of identical fibers, N_{ANF} and M_{VNLL}, respectively (Krips and Furst, 2009).



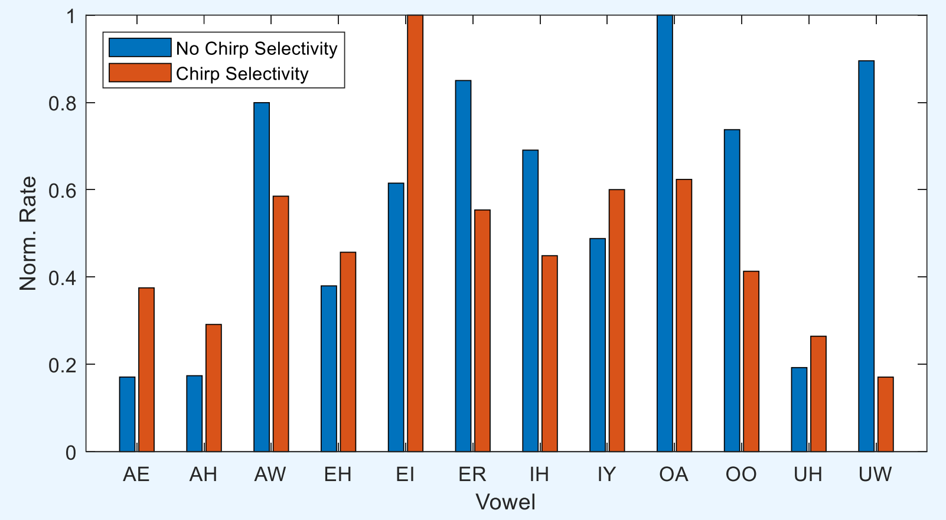
Discussion

- We describe a model for an IC cell with positive-velocity selectivity derived from an inhibitory direction-selective (DS) input.
- Possible sources of DS inhibition to the IC are octopus cells, which have both positive and negative selectivity (Lu et al., 2022). Octopus cells are sensitive to sequences of multi-frequency subthreshold inputs of varying amplitude, due to membrane dynamics of low-threshold potassium channels that can be simulated using a Hodgkin-Huxley style model.
- The IC model here is limited by our coincidence-detector-based strategy, but serves as a proof-of-concept for octopus-cell-based inhibition as the basis of chirp direction selectivity in the IC.
- Motivation: Chirp-sensitivity would affect IC rate-representation of complex sounds, including vowels. Below, vowel responses of chirp-insensitive and chirp-sensitive IC models are compared. Both neurons have CFs = 1 kHz and similar MTFs.
- Future work will focus on implementing a physiological model of chirp sensitivity to improve the prediction of IC speech responses.

Chirp-Insensitive Model MTF



Model Vowel Response Rates



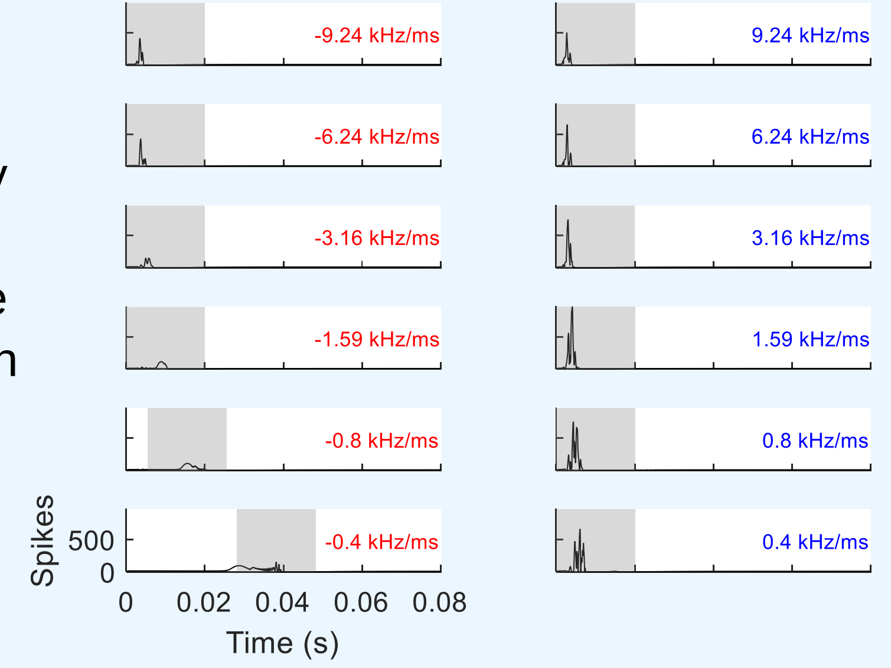
Results

By leveraging traveling-wave latency differences across frequency inputs, we can produce a simple DS model with an RVF that has positive velocity selectivity

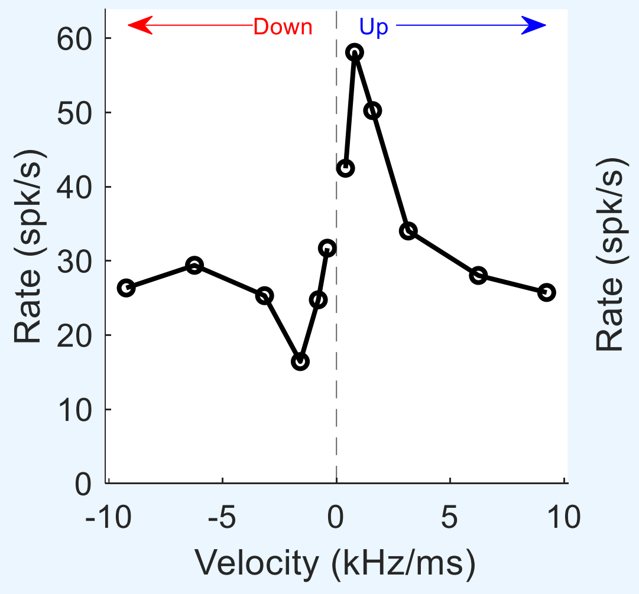
DS Model Cell

f_{CF} = 1 kHz
f_{off} = 4 kHz
N_{ANF} = 1
Δ_{DS} = 0.5 ms

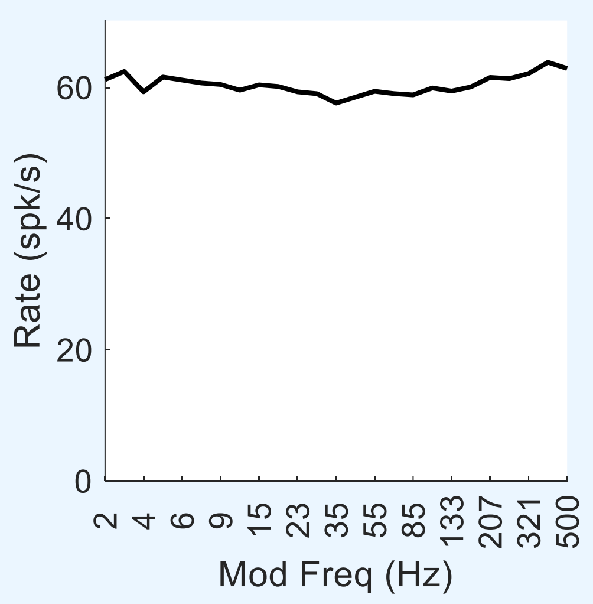
Chirp PSTH



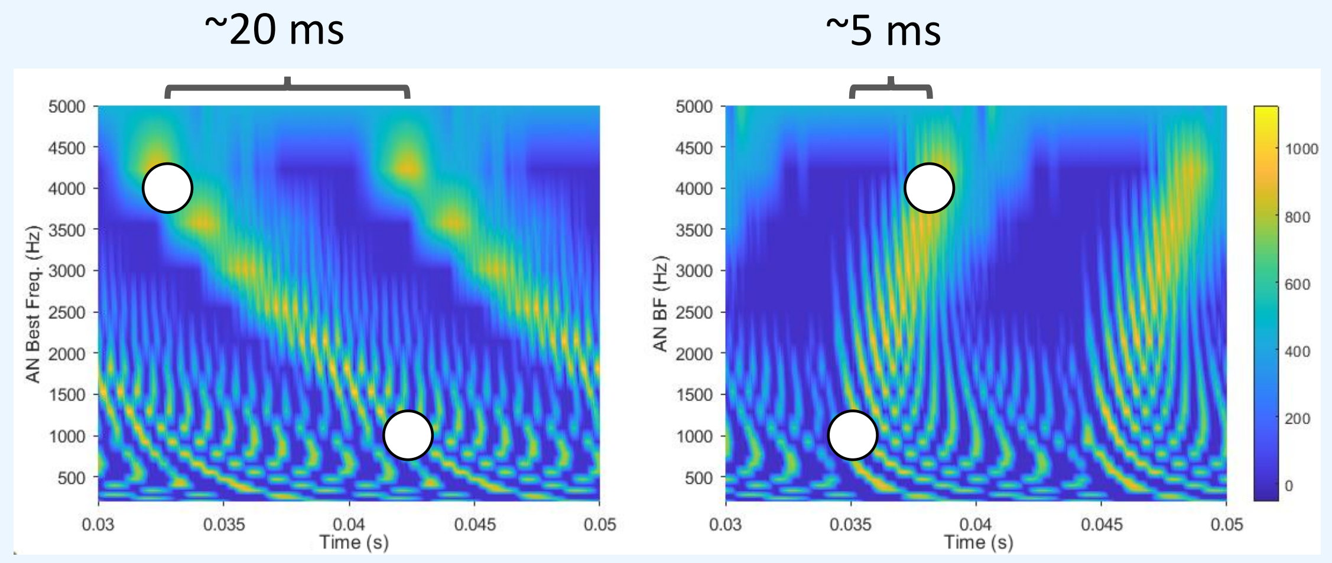
RVF



MTF



AN neurograms of Schroeder-chirp responses (UR Ear), illustrating how cross-frequency coincidence changes with chirp direction. (Left: Downward chirp; Right: Upward chirp)

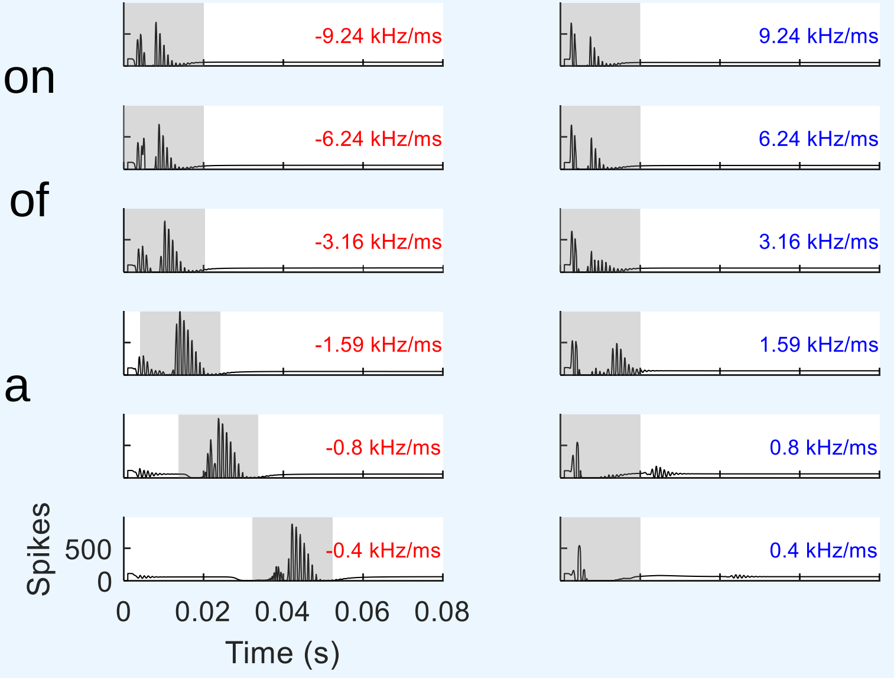


Direction-selective inhibition to an IC model yields an RVF with direction selectivity opposite to that of the inhibitory input. The IC model also has a band-enhanced MTF

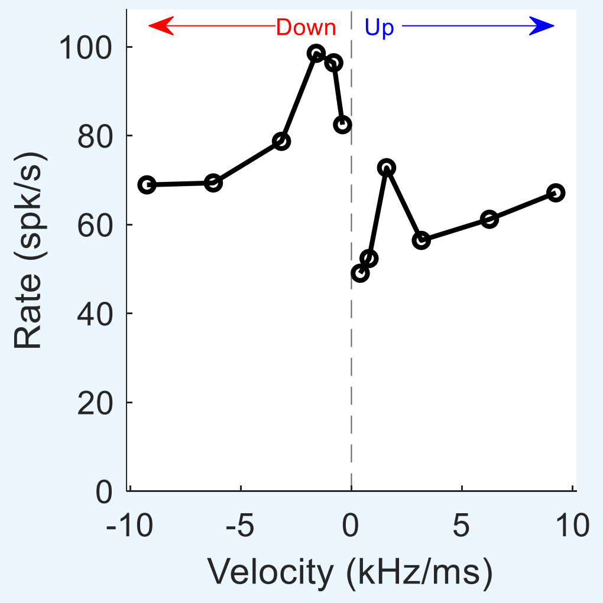
IC Model Cell

f_{CF} = 1 kHz
τ_{VNLL} = 2 ms
M_{VNLL} = 50
Δ_{IC} = 1 ms

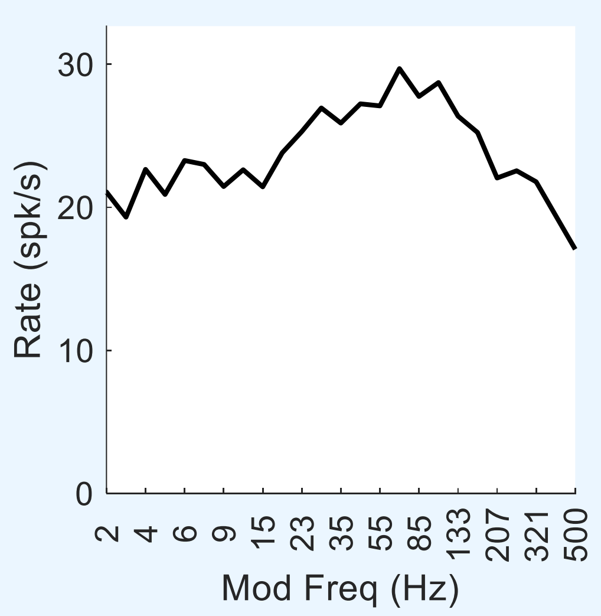
Chirp PSTH



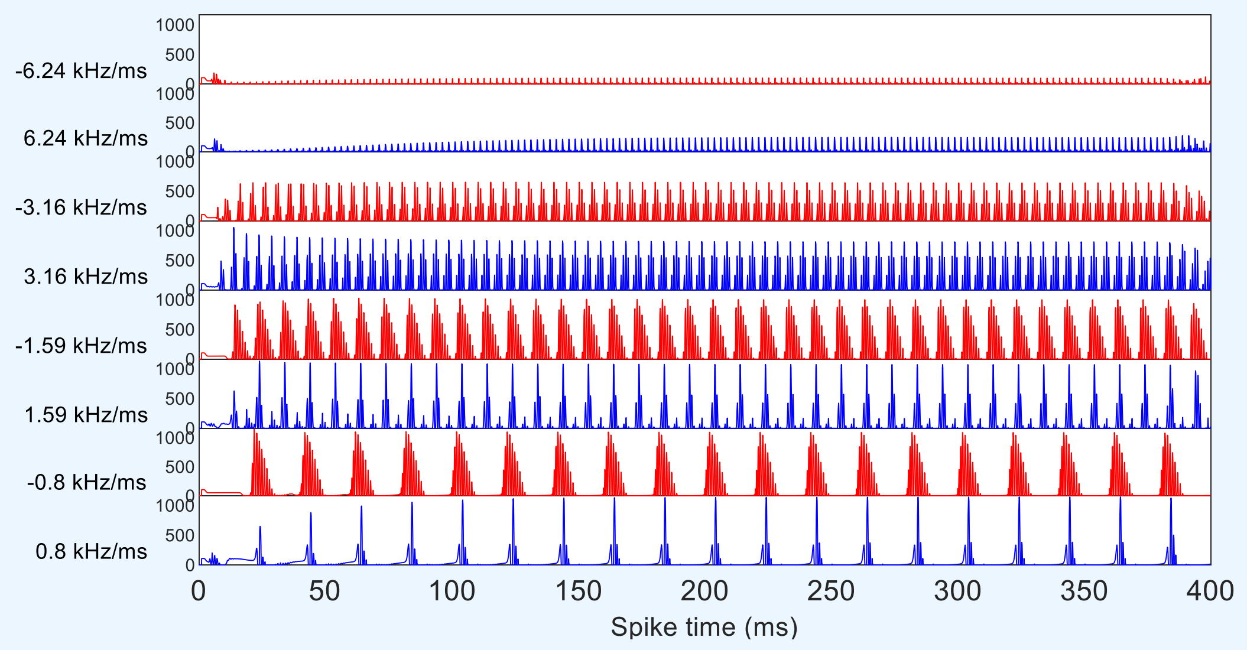
RVF



MTF



IC Model Schroeder PSTHs



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Supported by NIH-DC001641 and NIH-F31DC019816

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