Excitation and Inhibition in Bat Azimuthal Echolocation

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ABSTRACT

Bats use interaural level differences (ILD) as their primary cue for azimuthal echolocation. ILD information is processed in the bat's brainstem through cells that receive excitation from one ear and inhibition from the other ear (called EI cells). In this paper, we model bats' three ILD processing centers - the lateral superior olive (LSO), the dorsal nucleus of the lateral lemniscus (DNLL) and the inferior colliculus (IC), with a three layer feedforward spiking neural network. We also present a very large scale integrated (VLSI) circuit based neuromorphic system that mimics ILD processing in the bat LSO.

EXTENDED SUMMARY

Studies on sound localization have been traditionally focused on the interaural time difference, or ITD, due to its relative simplicity and applicability to many animals. Models of localization using ITD for the barn owl as well as for the human have been well developed and have been tested extensively. The bat's small head size and its use of high frequency sounds make the interaural level differences (ILD) the primary cue for its azimuthal echolocation. To date, however, models of localization using the ILD cue have used steady-state responses and do not address the role of spikes and short duration sounds. The short sonar vocalizations of bats (a few msec) and their fast flight speed (~2 m/sec), however, suggest that the auditory system of the bat does not have the time to average spikes over time. Neurons in the brainstem typically fire only one or two spikes in response to an echo. This strongly suggests that it is the population response of these neurons and perhaps the timing, or latency of these spikes that encode the information about the target.

In bats, ILDs are first encoded by neurons in the lateral superior olive (LSO). The LSO receives its principal excitatory inputs from the ipsilateral ear and inhibitory inputs from the contralateral ear. The encoded ILD information is further processed by the dorsal nucleus of the lateral lemniscus (DNLL) and the inferior colliculus (IC), which also contains a substantial population of ILD-sensitive neurons.

In this paper, we study how bats process ILD information in their brainstem using the so called "EI" (excitation and inhibition cell) cell. We apply Gerstner's Spike Response Model [2] to formalize a three layer feed forward spiking neural network that models the three ILD processing centers: LSO, DNLL and IC. Our model simplifies ILD computation at the LSO as a linear superposition of excitation and inhibition and a nonlinear shunting effect from inhibition when the membrane voltage is zero. Such a spiking neural model emphasizes the importance of timing between excitatory and inhibitory spike train, and the output of the LSO cell carries this timing information to the next stage. By studying different connections among neurons of the LSO, DNLL and IC as described in [1], we study how ILD information is further processed by the ascending network.

We have implemented part of the ILD network model through a very large scale integrated (VLSI) circuit system. Our neuromorphic azimuthal echolocation system consists of three parts: a sensory front-end that provides inputs to the LSO cell, a muticell LSO chip that generates population responses corresponding to different ILD inputs, and a back-end circuit that post-processes the LSO population response to drive a tracking motor system. The sonar front end transmits short 40 kHz pulses, receives, and processes the echo signals. The received echo signals are amplified, half-wave rectified and the envelopes are then extracted. The last stage of the front end is a spike generator that represents the aggregation of spikes from the population of anteroventral cochlear nucleus (AVCN) cells. The back-end extracts azimuth information from the LSO spike population response. The decoded azimuth information is then transformed into signals that control the motor tracking system. By understanding the neurobiological principles underlying echolocation, we hope to emulate the efficient implementation demonstrated in nature.

References

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