Axonal Conduction Delay Shapes the Precision of the Spatial Hearing in A Spiking Neural Network Model of Auditory Brainstem

Ben-Zheng Li, Member, IEEE, Sio Hang Pun, Member, IEEE, Mang I Vai, Senior Member, IEEE, Achim Klug, and Tim C. Lei

Abstract—One method by which the mammalian sound localization pathway localizes sound sources is by analyzing the microsecond-level difference between the arrival times of a sound at the two ears. However, how the neural circuits in the auditory brainstem precisely integrate signals from the two ears, and what the underlying mechanisms are, remains to be understood. Recent studies have reported that variations of axon myelination in the auditory brainstem produces various axonal conduction velocities and sophisticated temporal dynamics, which have not been well characterized in most existing models of sound localization circuits. Here, we present a spiking neural network model of the auditory brainstem to investigate how axon myelinations affect the precision of sound localization. Sound waves with different interaural time differences (ITDs) are encoded and used as stimuli, and the axon properties in the network are adjusted, and the corresponding axonal conduction delays are computed with a multi-compartment axon model. Through the simulation, the sensitivity of ITD perception varies with the myelin thickness of axons in the contralateral input pathways to the medial superior olive (MSO). The ITD perception becomes more precise when the contralateral inhibitory input propagates faster than the contralateral excitatory input. These results indicate that axon myelination and contralateral spike timing influence spatial hearing perception.

I. INTRODUCTION

The ability to locate the origin of sounds is critical for animals to survive in the wild. The sound localization pathway is involved not only in sound localization per se but also our ability to separate a sound source of interest from background noises [1]. Alterations in this pathway in a number of medical conditions such as autism or one form of age-related hearing loss disallow an affected person to function in such environments. It is therefore imperative to study both the healthy localization pathway in order to better understand it, such that we can properly evaluate the effects that alterations have on the functioning of the circuit. In mammalian hearing, sound localization is achieved by analyzing intensity and time differences that the same sound produces when arrives at the two ears. These interaural intensity and time differences vary systematically along the azimuth, providing a neural interpretation for the sound localization circuit to pinpoint the sound origin on the azimuth. Interaural intensity differences are suitable to localize high-frequency sounds, which interaural time differences are suitable to localize low frequencies. This report focuses on the latter binural neurons in which medial superior olive (MSO) process interaural time differences (ITDs) of low frequency sounds over a microsecond-order timescale, making this neural circuit one of the most temporally precise neuronal circuits in the mammalian brain [1] [2]. During this process, the neural activity generated from the two cochleae propagates initially in separate monaural neural circuits and eventually converges onto binaural neurons in the MSO. How the sound localization circuit accomplishes the micro-second precise integration of the two sets of signals across multiple fiber bundles, synapses, and neuronal types, is not entirely clear [1][3].

For a precise coincidence detection, action potential timing needs to be well tuned, despite there are several internal delays generated in the sound localization circuit. These include cochlear delays, synaptic delays, post-synaptic integration delays, and spike propagation delays [2]-[4]. Interestingly, some studies observed that the contralateral excitatory and inhibitory inputs to MSO differ in their axon morphology and conduction velocity [2][4][5], suggesting that these axons and contralateral propagation delays in the circuit might be specifically tuned to input timing and may contribute to the spatial hearing perception [3].

On the one hand, the contributions of precise contralateral inhibition to ITD coding have been investigated in several existing models of single MSO neurons [6]-[9], but these studies largely focused on the post-synaptic integration and cellular morphology in MSO neurons rather than an analysis of other involved nuclei and projections in the circuit. Additionally, previous network models of mammalian sound localization circuits [10][11] commonly symbolized the propagation delays as a constant without considering the differences in axon morphology; they also simplified the medial nucleus of the trapezoid body (MNTB) as a simple relay, making these models incapable of handling detailed temporal dynamics. Some other network models [12][13]

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tuned spike timing through the propagation delays, but their models employed the delay line structure mimicking the Jeffress model which is inconsistent with in-vivo data in mammals [6].

To investigate how those axonal properties and action potential timings affect sound localization precision, we developed a spiking neural network (SNN) model of the mammalian auditory brainstem with a more detailed architecture and variable axon myelination patterns. Through the simulation, we found that the axon myelination in contralateral pathways to MSO influences ITD perception sensitivity. The relatively thicker myelin in the contralateral inhibitory pathway makes the travel of the contralateral inhibition faster than the excitation, and this leading contralateral inhibition results in a more precise sound localization perception.

II. METHODS

A. Network Architecture

The sound localization circuit in the mammalian auditory brainstem contains several neural processing centers, as shown in Fig. 1a. The cochlear nuclei (CN) receive the cochlear responses to acoustic stimulation through the auditory nerve (AN). The spherical bushy cells (SBCs) in the CN excite the ipsilateral lateral superior olive (LSO) and both bilateral medial superior olives (MSO). The medial nucleus of the trapezoid body (MNTB) receives excitatory input from the globular bushy cells (GBCs) in the contralateral CN and sends inhibitory projections to the ipsilateral LSO and MSO. Besides, MSO also receives an ipsilateral inhibitory input from the lateral nucleus of the trapezoid body (LNTB) driven by the GBCs. For binaural cues, the MSO processes microsecond differences in the arrival time of low-frequency sounds, i.e., interaural time difference (ITD), and requires higher precision of spike timing comparing to the LSO that computes the differences in the arrival time of low-frequency sounds, i.e., GBCs. For binaural cues, the MSO processes microsecond differences.

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![Figure 1. Circuit schematics of (a) mammalian sound localization circuits in auditory brainstem; (b) the SNN model for ITD detection.](image)

The architecture of the proposed SNN model (Fig. 1b) consists of MSO and involved nuclei. Each neuron group consists of 1000 spiking neurons with the characteristic frequency equal to the frequency of the sound stimuli. The detailed parameters of the architecture are listed in Table I. Neurons between different neural populations were randomly connected with certain probabilities taken from previous studies [11] [14] [15].

![Figure 1. Circuit schematics of (a) mammalian sound localization circuits in auditory brainstem; (b) the SNN model for ITD detection.](image)

The spike generators in AN stimulate the network with the encoded sound signals. Those signals were made from 300 Hz 50 dB SPL (sound pressure level) pure tones lasting 100 ms with 20 ms ramp-up and ramp-down, and released to two ears at different times with ITDs ranging from -1 ms to +1 ms. A peripheral hearing model [16] [17] was used to encode the sound waves into the AN’s neural activities. The AN composites auditory nerve fibers in three spontaneous firing rates with a proportional ratio of 6:2:2 for high, medium, and low spontaneous rate fibers.

### Table I. List of Parameters for Network Architecture

<table>
<thead>
<tr>
<th>Population</th>
<th>Type</th>
<th>Connection</th>
<th>Connectivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>AN</td>
<td>Spike generator</td>
<td>AN → ipsi. GBC</td>
<td>4 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AN → ipsi. SBC</td>
<td>4 %</td>
</tr>
<tr>
<td>SBC</td>
<td>Excitatory</td>
<td>SBC → ipsi. MSO</td>
<td>0.6 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SBC → cont. MSO</td>
<td>0.6 %</td>
</tr>
<tr>
<td>GBC</td>
<td>Excitatory</td>
<td>GBC → ipsi. LNTB</td>
<td>0.6 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GBC → cont. MNTB</td>
<td>0.1 %</td>
</tr>
<tr>
<td>MNTB</td>
<td>Inhibitory</td>
<td>MNTB → ipsi. MSO</td>
<td>0.3 %</td>
</tr>
<tr>
<td>LNTB</td>
<td>Inhibitory</td>
<td>LNTB → ipsi. MSO</td>
<td>0.6 %</td>
</tr>
<tr>
<td>MSO</td>
<td>Excitatory</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table II. List of Parameters for Neuron and Synapses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$C_m$</td>
<td>70 pF</td>
<td>$E_e$</td>
<td>0 mV</td>
</tr>
<tr>
<td>$V_{th}$</td>
<td>-50 mV</td>
<td>$E_i$</td>
<td>-70 mV</td>
</tr>
<tr>
<td>$V_{reset}$</td>
<td>-55.8 mV</td>
<td>$\Delta g_e$</td>
<td>15 nS</td>
</tr>
<tr>
<td>$\tau_{ref}$</td>
<td>5 ms</td>
<td>$\Delta g_i$</td>
<td>55 nS</td>
</tr>
<tr>
<td>$E_i$</td>
<td>-55.9 mV</td>
<td>$\tau_e$</td>
<td>0.23 ms</td>
</tr>
<tr>
<td>$g_i$</td>
<td>13 nS</td>
<td>$\tau_i$</td>
<td>2 ms</td>
</tr>
</tbody>
</table>
The ipsilateral connections include a normally distributed synaptic delay of $0.4 \pm 0.05$ ms (mean ± standard deviation), and the contralateral connections traveling across the midline involves axonal conduction delays computed from different myelination properties using a multi-compartment axon model [4] [18].

C. Data Analysis

Responses of a neuron to ITDs were represented as the firing rate during the sound stimulation. Moreover, each neuron's ITD responses were smoothed using a Gaussian filter with a window of +/-100 $\mu$s ITDs. The simulation was repeated 30 times with different random seeds to compensate for the random effects induced during the sound stimuli encoding and the network connection. The nucleus's ITD response was computed as the mean ITD responses of all neurons from the nucleus across all random permutations.

The sensitivity to ITDs was estimated by the just noticeable difference (JND) which describes the shortest perceptible change of ITDs. The JNDs are calculated by comparing responses between symmetric ITDs, e.g. +/- 20 $\mu$s. The difference of firing rates between left and right MSOs under symmetric ITDs were computed for each random permutation and then compared using a one-tailed Mann-Whitney U test. The JND was defined as the smallest ITD that reaches the minimum significance.

III. RESULTS

To elucidate the relationship between axon myelinations and conduction delays, the conduction velocities were computed under various internode lengths ($L$) and myelin thicknesses ($d$). The results in Fig. 2 show that the conduction velocity is proportional to the thickness of the myelin sheath. The myelin thickness was tuned under a fixed internode length ($L = 0.2$ mm) to obtain different axon conduction velocities in the following analyses.

The results of network simulation indicate that the ITD perception is more precise when the GBC fiber has thicker myelin comparing to the SBC fiber, and the contralateral inhibition propagates faster than the excitation (shown in Fig. 3). For details, the axon myelination of SBC and GBC fibers influences the ITD perception in different ways. The peak amplitude and location of ITD tuning curves vary with the myelin thickness of SBC fiber and the peak width changes with GBC fiber.

![Figure 2. Axon myelination and conduction velocity: (a) schematic of axon myelination; (b) axonal conduction velocity versus myelination thickness; (c) axonal conduction velocity versus internode length.](image2)

![Figure 3. Neural responses to ITDs differs from the relative myelin thickness: (a-d) neural responses with thicker GBC fiber myelin ($d_{GBC} = 0.165$ $\mu$m, $d_{SBC} = 0.487$ $\mu$m); (e-h) neural responses with equal myelin thickness ($d_{GBC} = d_{SBC} = 0.487$ $\mu$m); (i-l) neural responses with thicker SBC fiber myelin ($d_{GBC} = 1.032$ $\mu$m and $d_{SBC} = 0.487$ $\mu$m). Listed responses includes the MSO neuronal ITD responses (a, e, i), ITD tuning curves (b, f, j), differences of firing rates between right and left MSO (c, g, k), and the noticeable ITD ranges (d, h, l).](image3)
smaller JNDs of the ITD and more sensitive ITD perception (Fig.4).

IV. DISCUSSION

The computational modeling results illustrate the influence of axon properties and contralateral spike timing on the ITD perception, supporting the critical role of axon myelination and contralateral inhibition in ITD tuning at the circuit-level.

In our model, the conduction velocities of contralateral inputs to MSO were tuned by adjusting the myelin thickness on contralateral projections. With the thicker myelin layers on the GBC projection, the contralateral inhibition precedes the excitation, and the ITD responses became more sensitive and precise. This result is consistent with previous experimental and computational findings at the cellular level [2] [4] [6] [7] [9] and implies the axonal morphological adaptation on the contralateral inhibitory pathway accelerating the inhibition and modulating the ITD precision.

Our current model only discusses pure-tone stimulation with a single frequency and intensity level. How much the observed phenomenon would be affected by multiple frequencies and sound levels remains to be tested. The model will be further developed with the Hodgkin-Huxley-based neuron model to analyze the sound localization circuit's temporal dynamics under more complicated settings, as the previous studies had also reported the implementation of spiking neural models under complex sound stimuli like speeches [11] and reverberating echoes [19].

V. CONCLUSION

The effects of axon properties and spike timing on spatial hearing perception have been examined using the proposed SNN model of the auditory brainstem. The simulation results indicate that the axon myelination and propagation delays on the contralateral pathways to the MSO shaped the ITD tuning. The thicker myelin layers on the contralateral inhibitory pathway speed up the contralateral inhibition and sharpen the precision of ITD perception.

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