The song motor pathway in birds: a single neuron initiates a chain of events that produces bird sounds with realistic spectra properties

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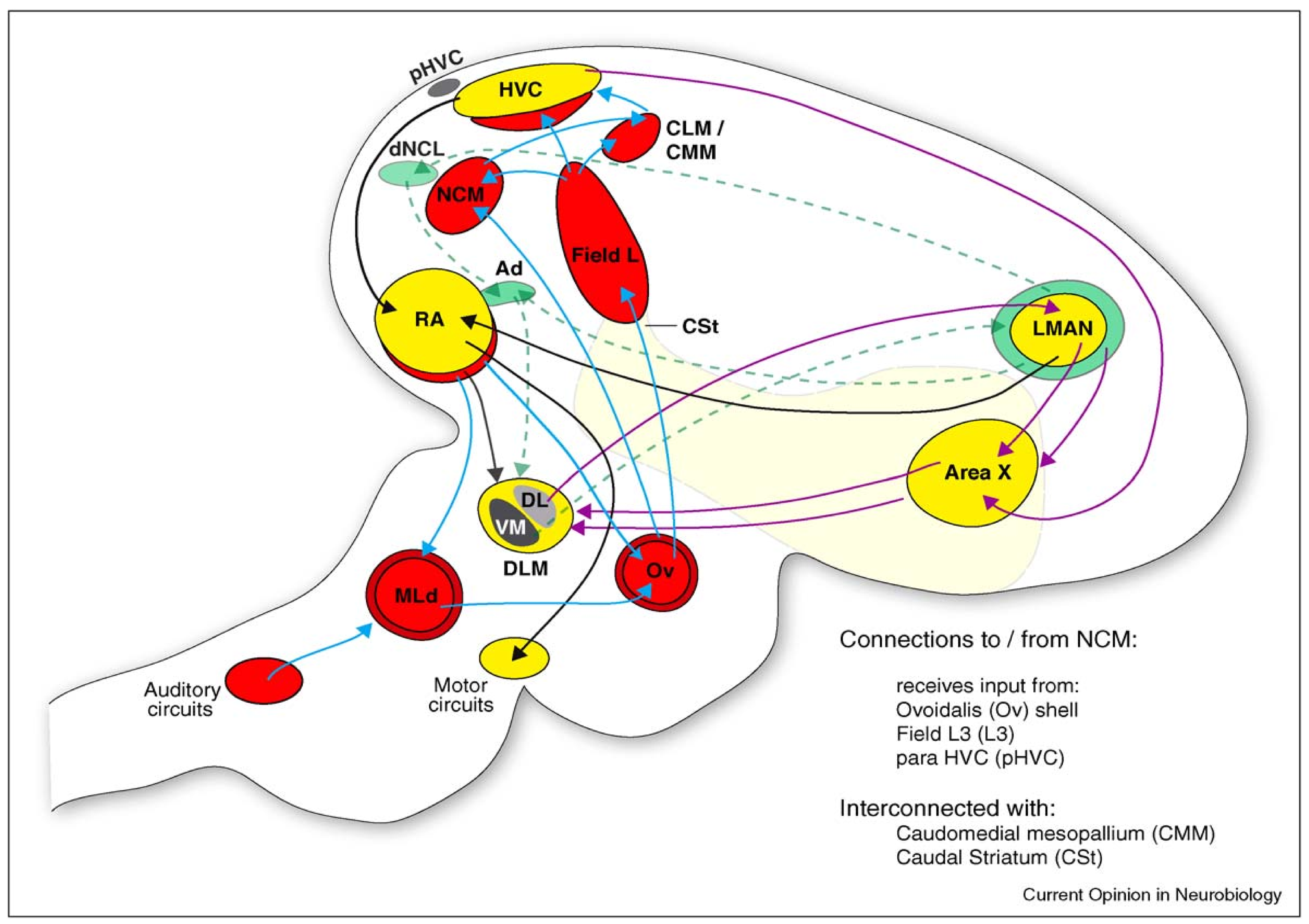
Summary

Birdsong is a complex learned behavior regulated by Neuromuscular coordination of different muscular sets, necessary for producing relevant sounds. We developed a neural network representing the pathway from the High Vocal center (**HVc**) to the robust nucleus of the archistriatum (**RA**) neurons that drive the muscles to generate sounds. We show that a single active neuron is sufficient to initiate a chain of spiking events that result to excite the entire network system. The network could synthesize realistic bird sounds spectra, with spontaneous generation of intermittent sound bursts typical of birdsong (song syllables). This study confirms experiments on animals or on human, where results have shown that single neurons are responsible for the activation of complex behavior or are associated with high level perception events.

Birdsongs production

Birds use acoustic signals for communication purposes and birdsong is known to play a prominent role in sexual selection by influencing female preferences and for territorial defense [Catc 2008]. This is a very complex behavior regulated by different hormonal and neural mechanisms that interact in an intricate and hierarchical way [Catc 2000, Catc 2008, Brainard 2002]. Birdsong production has been studied for long time, and we know that it is a vocal sound produced via phonation through pneumatically induced vibrations [Bradbury 2011]. In addition, we learned that songbirds modulate their vocal tract to filter and produce sounds at different frequencies [Brainard 2002]. Given that the sound generation involves modulation of the vocal tract and the coordination of breathing patterns in such a way that the syringe receives airflow to vibrate and produce consistent sounds [Podos 2009, Wild 1997], birdsong requires a highly coordinated neuromuscular activity to produce sounds of high quality.

Birdsong production involves mainly three different muscular sets: upper vocal tract, syringe and respiratory system [Nottebohm 2005]. Previous studies have determined that coordination of these muscular sets for song production, at least in songbirds that learn their song (Passeriformes: oscines), is possible by a group of brain nuclei and the connecting pathways [Brainard 2002, Nottebohm 2005]. The one responsible for song production is known as the motor pathway, and this neural architecture comprises the High Vocal centre (HVc), the Robust nucleus of the Archistriatum (RA) and the Tracheosyringeal Motor Nucleus [Brainard 2002, Nottebohm 2005 and 1976].



Schematic section of the songbird brain illustrating the classic song system (brain areas in yellow and connection arrows in black for the adult motor pathway and in purple for the basal-ganglia pathway). Auditory areas and areas implicated in song memorization are shown in red, connected by blue arrows. Also shown is a pathway parallel to the basal-ganglia pathway that was recently shown to be implicated in song learning, with brain areas depicted in green and connection arrows in dashed green lines.

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Izhikevich spiking network

By using mathematical models, previous studies have attempted to understand and emulate the spiking neural network that produces birdsong.

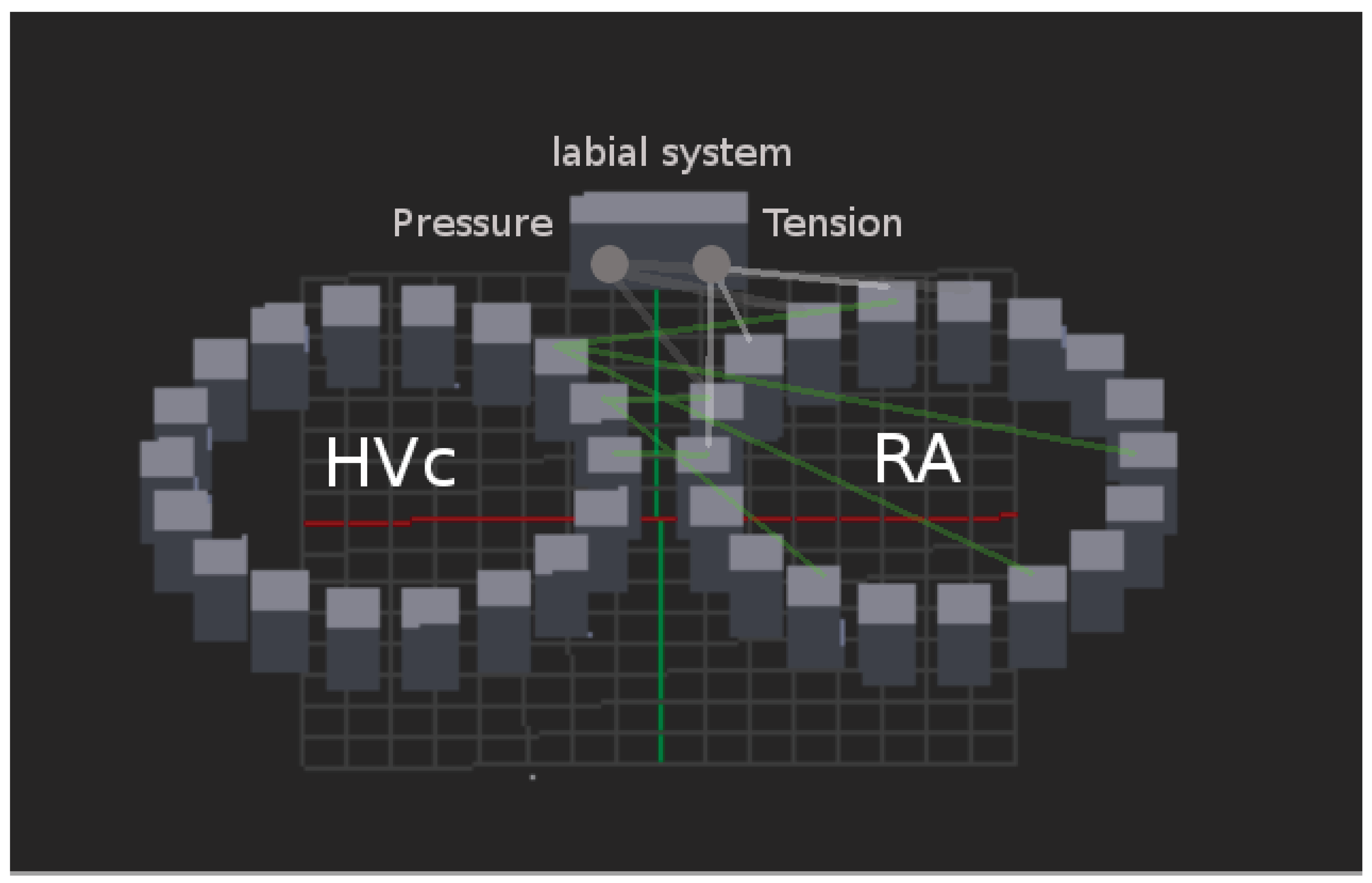
In this work we use most realistic and biological plausible network models (an **Izhikevich spiking network** to reproduce the neurological pathway from the High Vocal center (HVc) to the robust nucleus of the archistriatum (RA) that drives muscular tension for the bird labial oscillation.

In our tests neuronal connection structure is random (as neural connections are in real brains) and results are repeated and averaged over three test for reproducible outputs. The constant activity of one single neurons appears to be the causal entity that drives the complex behavior of the neural system that generate synthetic sounds. The sounds are studied an analyzed in their spectral characteristics, but also we converted them to digital waveform in ".wav" format. These synthetic songs are in this way playable with common digital means for audible sounds and those can be compared with real bird songs.

Our network model

In this study we implemented the neural stream that emulates the High Vocal center up to the nucleus of the Archistriatum. An object implemented in the language python represents each neuron. We use a very efficient type of leaky integrate and fire neuron model, developed by Izhikevich.

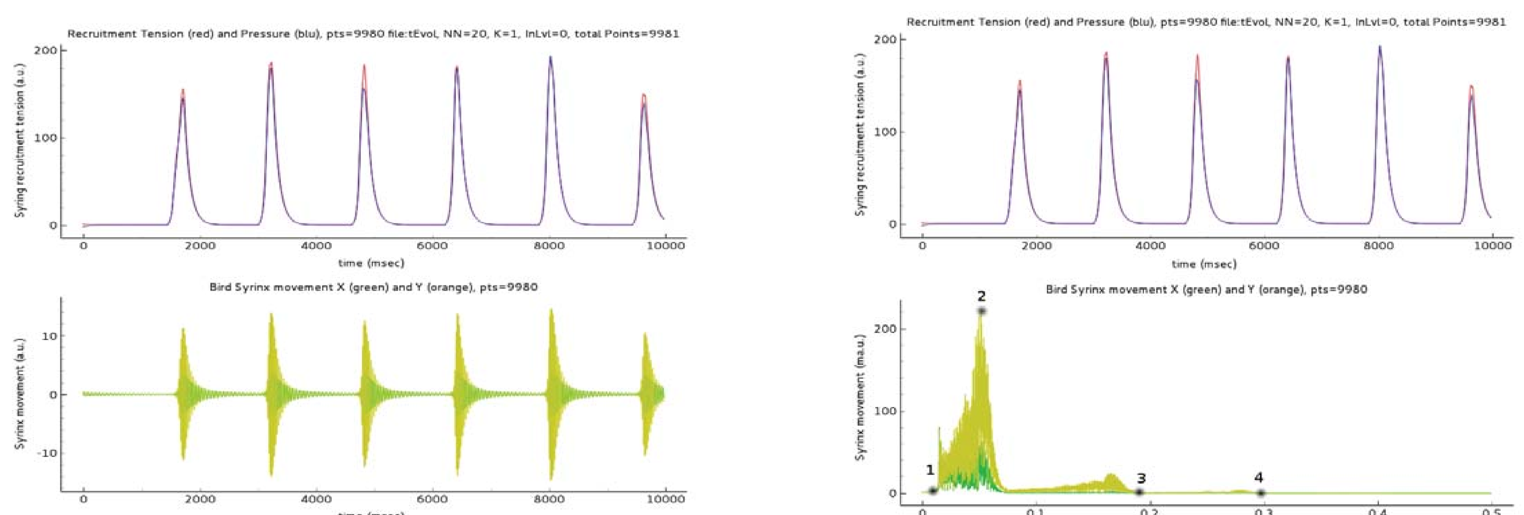
The two main variables taken into account are the intracellular membrane voltage V and the cell recovery potential U, four Izhikevich parameters (a=0.2, b=0.02, c=65 and d=8 for "regular spiking" RS neuron) describe the neuron type.



A graphical representation of the neural network used in this study.

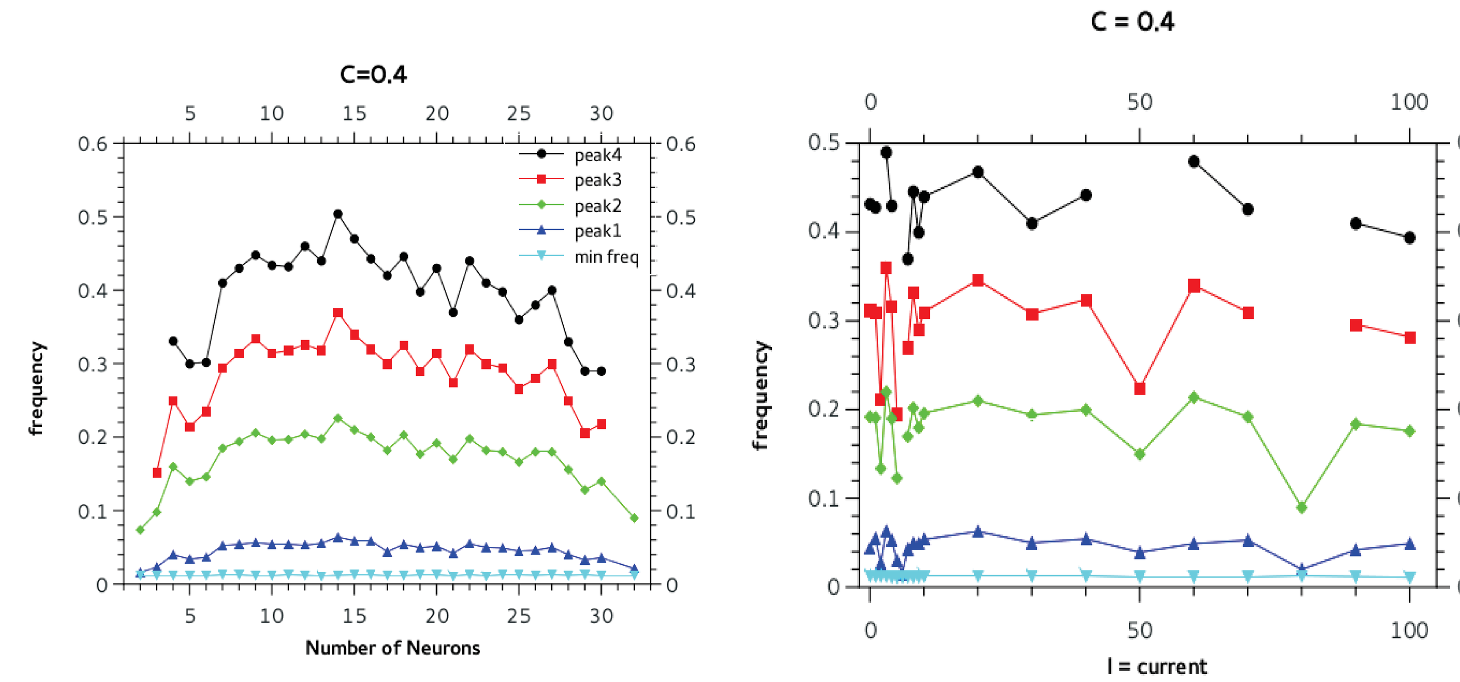
Experimental results

Simulation of the spiking neural network model

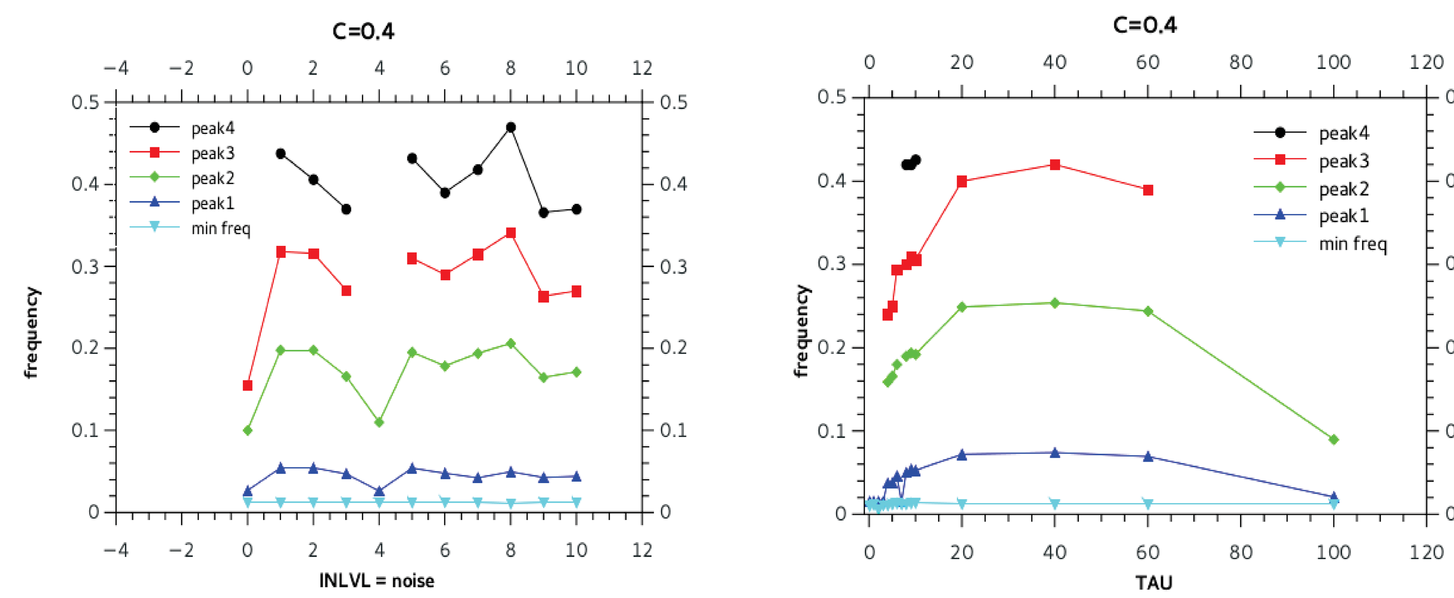


Burst of oscillations (left plot) produce spikes of pressure and tension (upper panel) that consequently generate oscillation of the syrinx (lower panel). Position of relevant frequencies in the birdsong spectrum (right plot, bottom) compared to the same pressure and tension curves (top panel).

Spectrum characteristics: network size and input current



Spectrum characteristics: current noise and decay of bronchial pressure



Conclusion

Our model and results concur with the idea that the expression of complex behaviors is generated by a synaptically connected chain of neurons. The spiking in our model is initiated by a single initiator neuron, which is followed by a stable propagation of bursts. In addition, similar to previous experiments on animals and models, activation of neurons occurs by a synchronous synaptic input coming from a group of neurons that has previously been activated.

This study suggests the existence of a simple extremely efficient mechanism for the generation of complex activity as birdsongs and paves the way for the complete simulation of such or more complex animal behavior with simple and primitive spiking networks instruments.

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