DUAL PATHWAY ARCHITECTURE UNDERLYING VOCAL LEARNING IN SONGBIRDS

Summer Internship Report

Abstract

Song acquisition and production in songbirds are managed by two neural pathways: the motor pathway for production and the basal ganglia (BG) pathway for learning. Juveniles learn by mimicking adult songs through trial and error, guided by dopaminergic signals. The complexity of neural control and syrinx musculature makes song teaching challenging. Although reinforcement learning (RL) is often suggested for sensorimotor learning, it can lead to sub-optimal solutions in continuous action spaces. A dual pathway architecture in avian vocal learning can help overcome these limitations. The BG pathway induces significant daily changes in vocal production for exploration, while the motor pathway consolidates these changes, similar to a simulated annealing process. Simulations on various performance landscapes show that this model, considering behavioural constraints, achieves optimal learning

Atharv Sagar Suryawanshi

IVR No: 202100041052

Scholarship for Higher Education (SHE) Component under INSPIRE

Format for Project Completion Certificate

(To be filled by the Supervisor of Research Project)

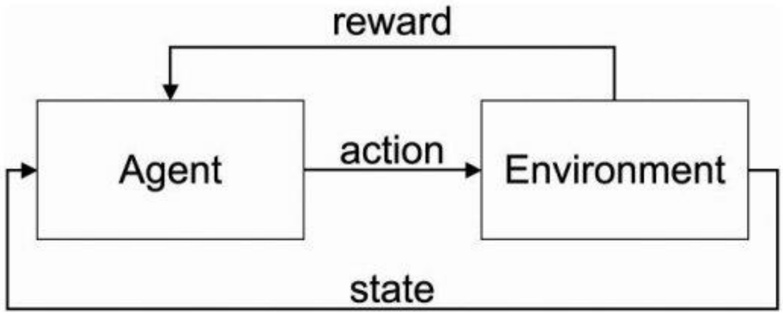
1. IVR Number or Application Ref. No. : 202100041052
2. Name of INSPIRE Scholar: Atharv Sagar Suryawanshi
3. Name of College where Scholar is studying: Indian Institute of Science
4. Name of University to which above College is affiliated: Indian Institute of Science
5. Bank Account Number of Scholar: 40666203960
6. IFSC Code: SBIN0002215
7. Mobile No. and Email Address of Scholar: 8080009347; atharvsagar@iisc.ac.in
8. Title of Project: Dual pathway architecture underlying vocal learning in songbirds
9. Broad Subject Area of Research Project: Computational Neuroscience
10. Project Duration (in weeks): 13 weeks
11. Date of Start of Research Project: 12th May 2024
12. Date of Completion of Research Project: 13th Aug 2024
13. Supervisor Name: Arthur Leblois
14. Designation of Supervisor:
15. Affiliation of Supervisor
    (a) Department: Institut des Maladies Neurodégénératives
    (b) University: University of Bordeaux
    (c) Address: 146 Rue Léo Saignat, 33000 Bordeaux, France
    (d) Mobile no. and Email Address: +33 5 33 51 47 98 ; arthur.leblois@u-bordeaux.fr
16. Major Specialization area of Supervisor: Basal Ganglia, Dopamine, Computational Neuroscience

(Signature of Supervisor)

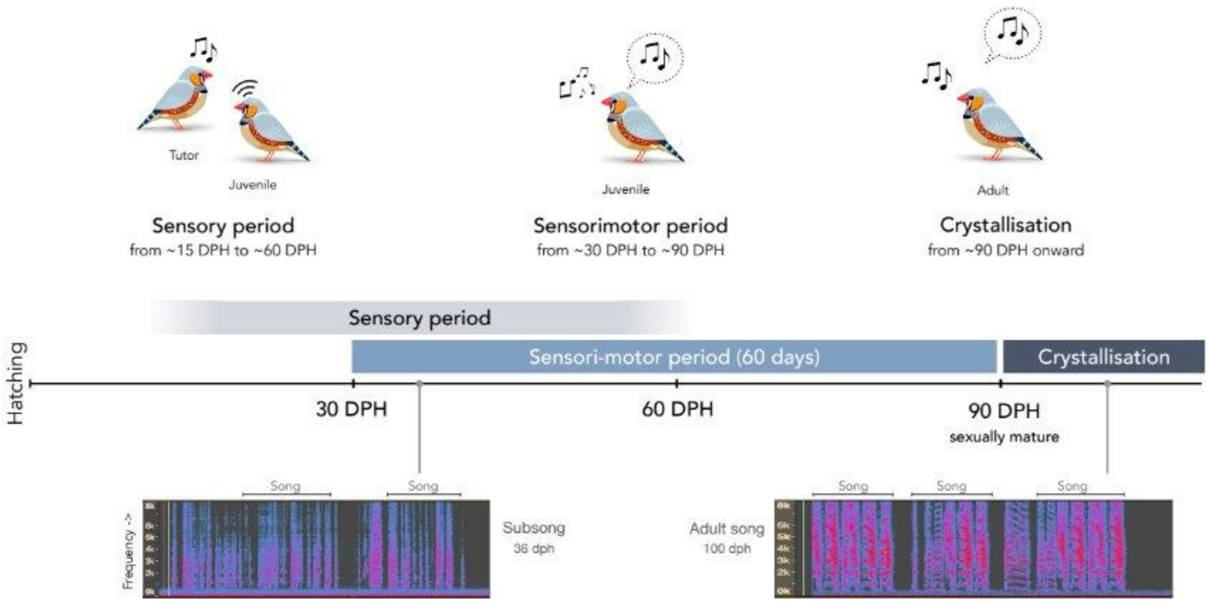
Date: 24/08/2024

Introduction

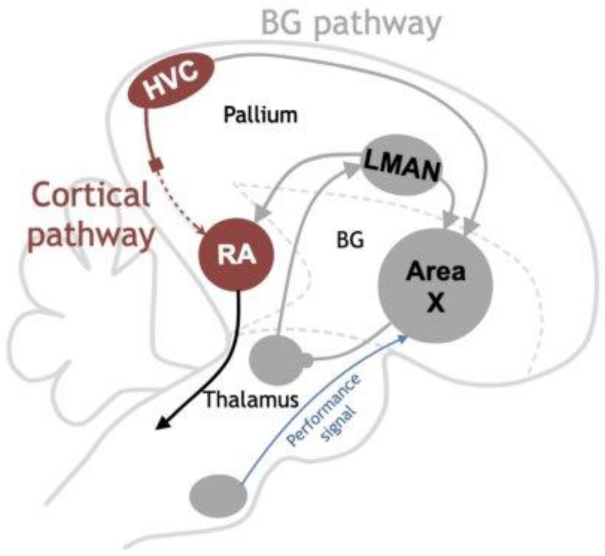
Motor skill acquisition in vertebrates is often attributed to reinforcement learning (RL), where skills are honed through trial and error. Each motor trial is evaluated in the sensory space, generating a reward signal that helps refine the action. This process aims to find the global optimum of the reward landscape. While RL through gradient ascent can fail due to local maxima, gradient-free algorithms like simulated annealing are more effective in complex landscapes, though their neural implementation remains speculative.



To explore sensorimotor learning mechanisms, we examine vocal learning in songbirds. We hypothesise that a dual pathway architecture, combining RL and noise regulation, governs motor learning. Our approach focuses on plausibility rather than optimality, starting from biological facts and exploring how neural circuitry might efficiently implement vocal learning.



Juvenile songbirds learn to imitate adult vocalisations through a process similar to human speech learning. This involves trial and error, with vocalisations evolving from variable babbling to accurate imitations over approximately 60 days. Changes occur at multiple timescales: rapid daily changes, weekly consolidations, and increased variability post-sleep.



The song system

Song production and learning are controlled by two neural pathways: the motor pathway for vocal production and the basal ganglia-thalamo-cortical (BG) pathway for learning and plasticity. The motor pathway connects the premotor HVC, which generates song timing, to the robust nucleus of the arcopallium (RA), which controls vocal muscles. The BG pathway matures early and drives initial vocalisations and variability, receiving performance evaluation signals via dopaminergic projections. This pathway induces motor biases that are gradually consolidated in the motor pathway. Post-learning, the motor pathway can produce the learned song independently of the BG pathway, although the BG pathway still influences residual variability.

During song learning, each timing signal in the HVC must be matched with the correct muscle configuration to produce the desired syllable, a complex task in a continuous action space due to the non-linear and redundant relationship between RA neural activity, muscle activation, and vocal acoustics.

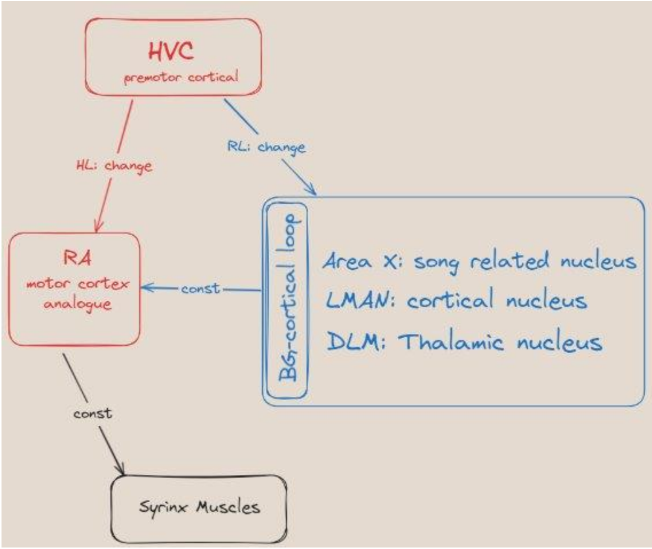
We propose leveraging the dual pathway architecture in birds to address the limitations of direct gradient descent approaches. By simulating a simplified algorithmic implementation of vocal learning across various reward landscapes, we show that the structural (delayed maturation of the cortical pathway) and functional plasticity (activity-dependent synaptic plasticity) in this two-pathway framework can overcome the shortcomings of standard RL approaches and enhance learning efficiency.

Methodology

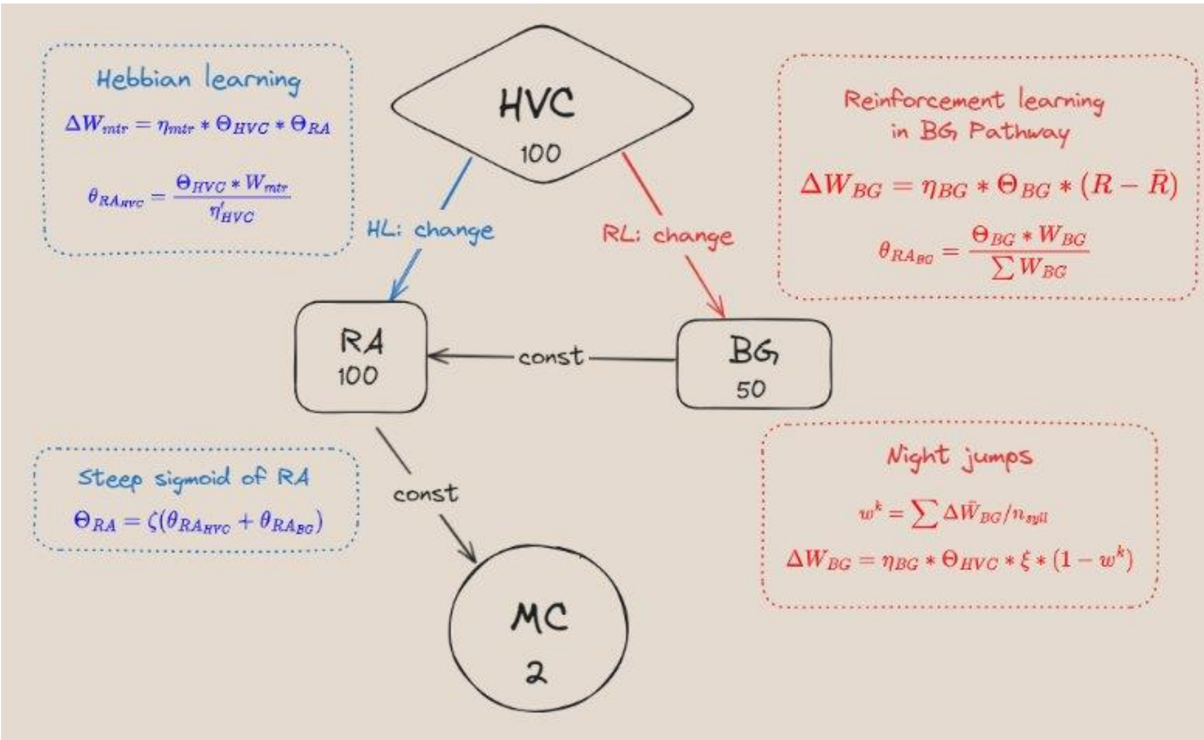
The model aims to replicate the vocal learning process in songbirds, aligning with behavioural, physiological, and anatomical evidence to gain insights into sensorimotor learning. We explore the interaction between the two parallel pathways in the song system and their role in song acquisition. This model uses a simplified two-dimensional (2D) representation of the dual pathway architecture to study its properties in a reduced system systematically.

Architecture

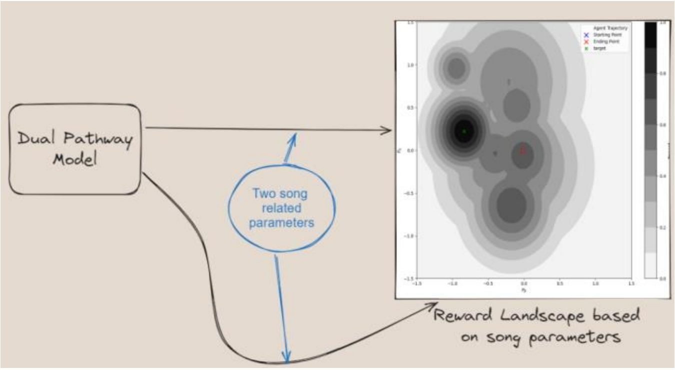
We designed a four-layer model representing HVC, RA, BG, and MC (motor control). These structures are interconnected: HVC and RA are linked directly and via the BG—RA projects to regions controlling respiration and syringeal muscles, represented by the MC layer.



The model scales neuron numbers proportionally to those in the song system, with HVC and RA having 100 units each and BG having 50. Each unit represents a population of inhibitory and excitatory neurons. RA neurons use steep sigmoid activation functions, bounding firing rates between -1 and 1, while BG neurons have linear firing rates within the same range. HVC and RA are fully connected, as are HVC and BG, with plastic weights based on activity-dependent plasticity. The BG-RA and RA-MC pathways are topographically clustered with fixed positive weights.



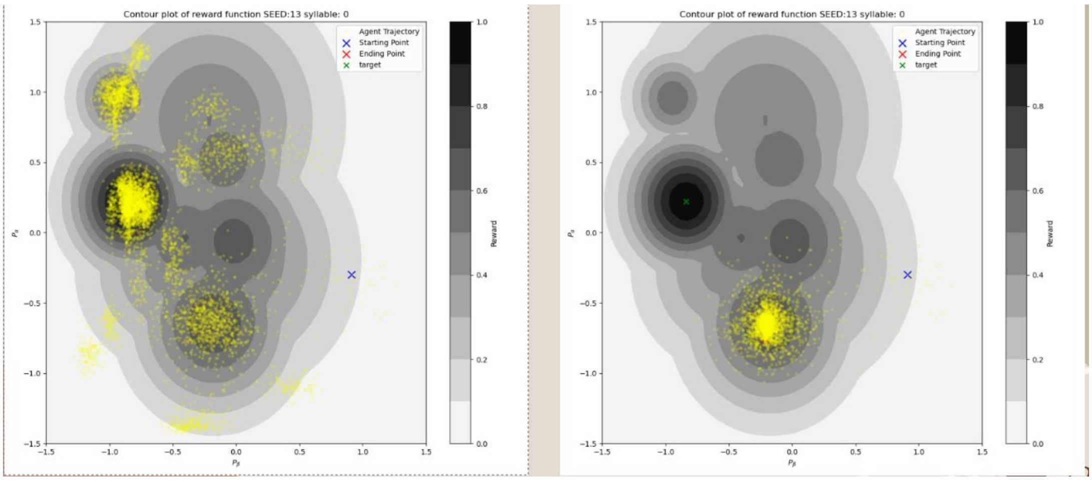
The motor output from the model is correlated with two song related parameters to form a 2D reward landscape where we can test the performance of the model as shown below.

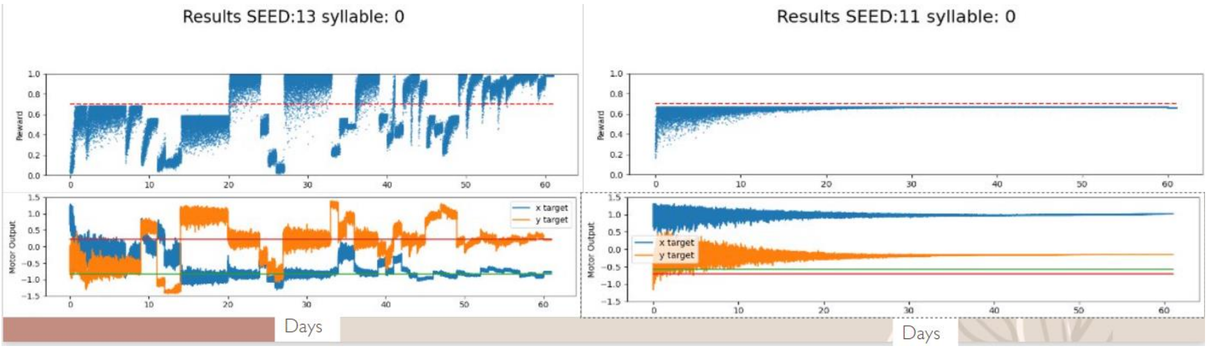


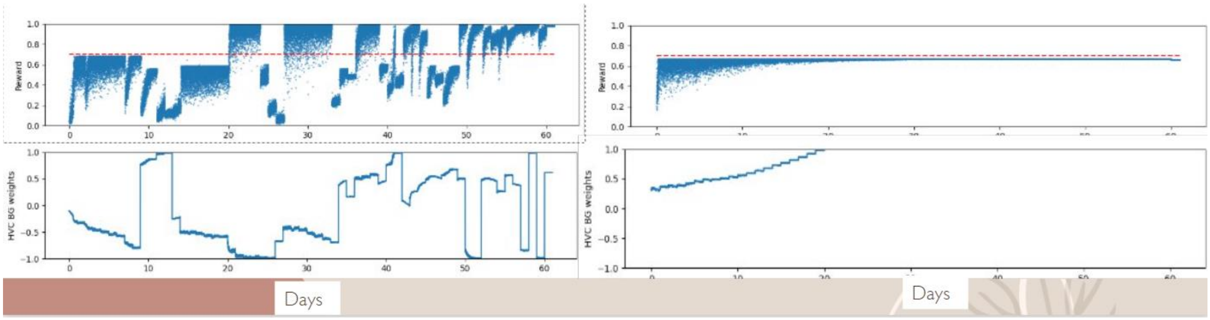
Analysis

With and without jumps

We compare learning with two different algorithms, one includes the nightly jumps and the other does not have nightly jumps.



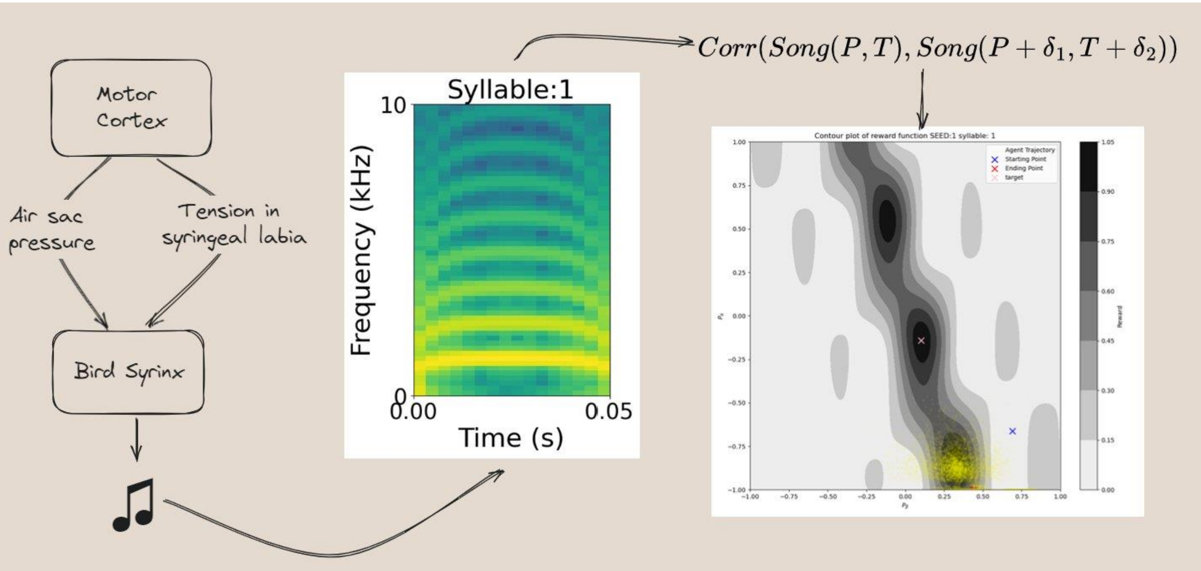


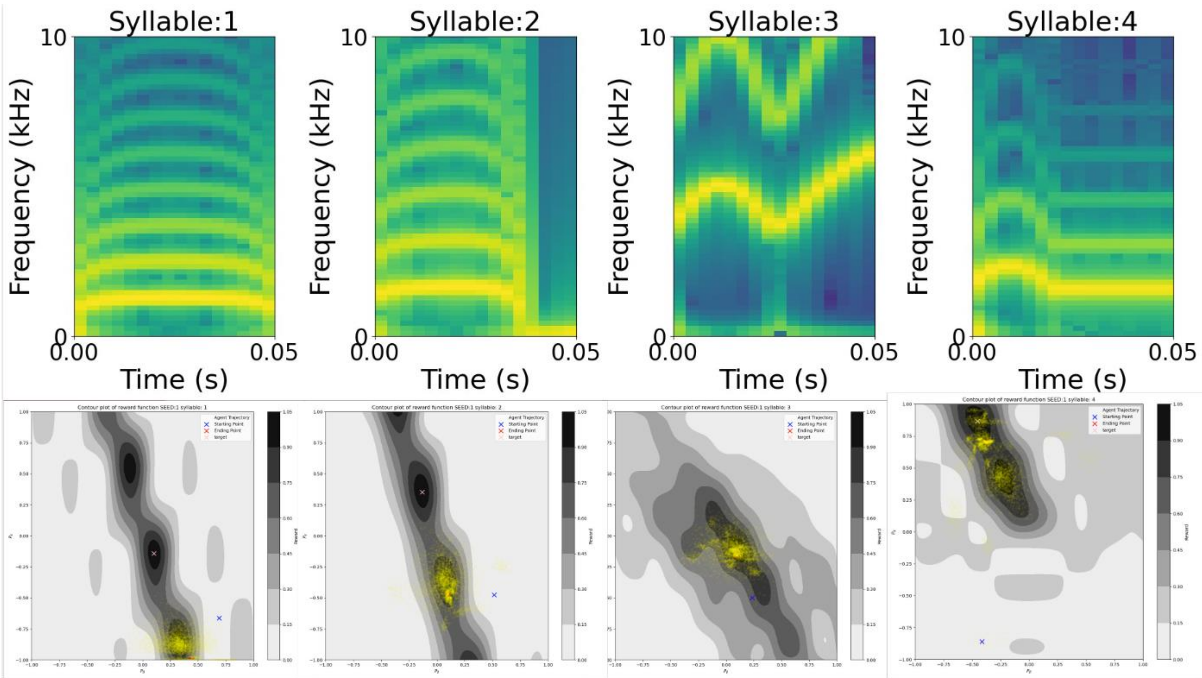


We observe that neural network model trained with nightly jumps performs better and does not get stuck in a local maximum.

Syrinx Based Contours

In order to relate these parameters with an actual song, we look at two song parameters, namely pressure in the air sac and the tension in syringeal labia. These two parameters are used to produce a bird song. We create a syllable spectrogram using these two parameters. Now We slightly modify these parameters and compare the new and original spectrogram to make a 2D reward landscape.

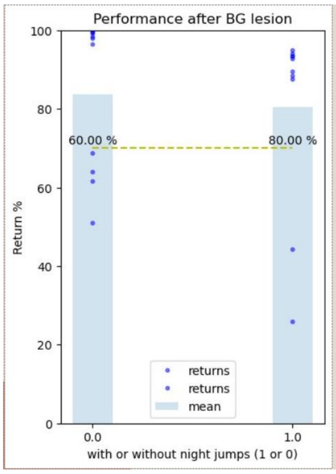


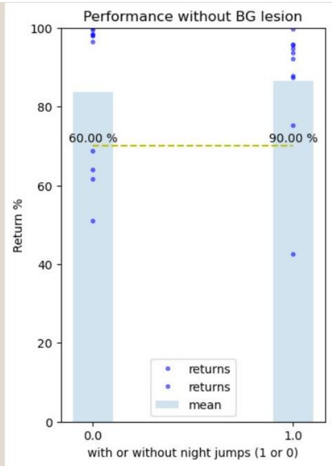


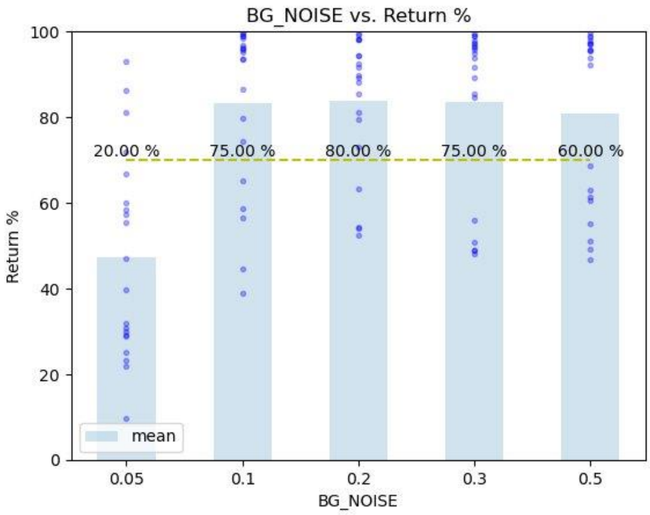
Reward landscapes for four different syllables

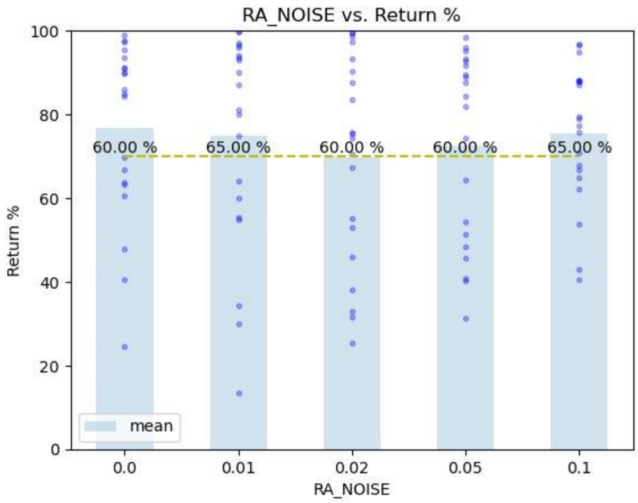
Robustness tests

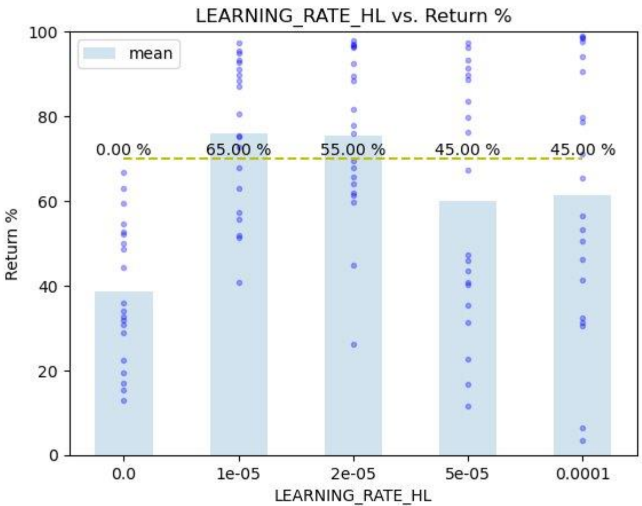
Here we test how does the model fare for different parameter values.

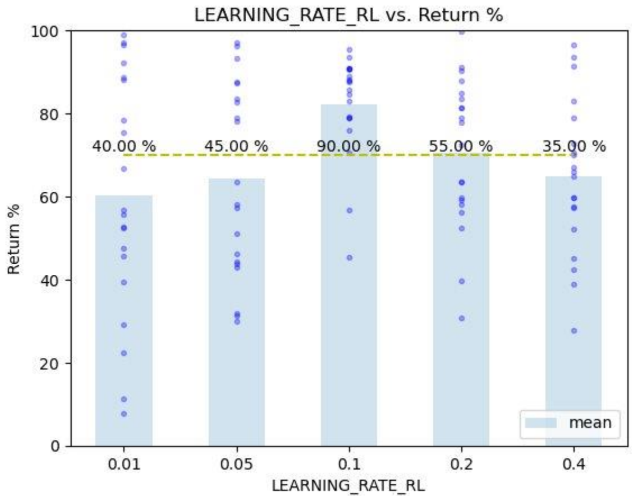

Performance after BG lesion
60.00 %
80.00 %
Return %
with or without night jumps (1 or 0)
returns
returns
mean

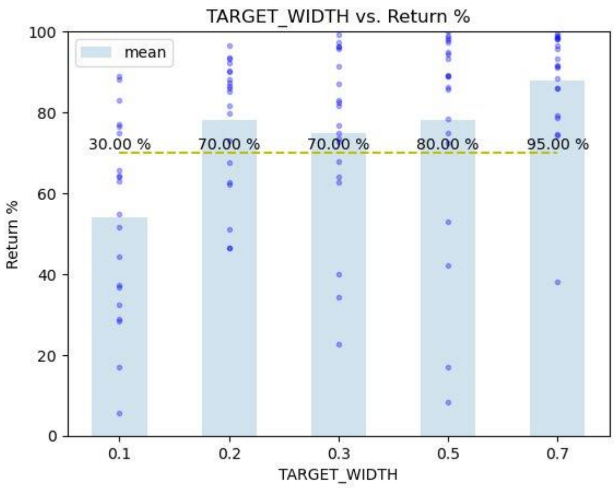

Performance without BG lesion
60.00 %
90.00 %
Return %
with or without night jumps (1 or 0)
returns
returns
mean

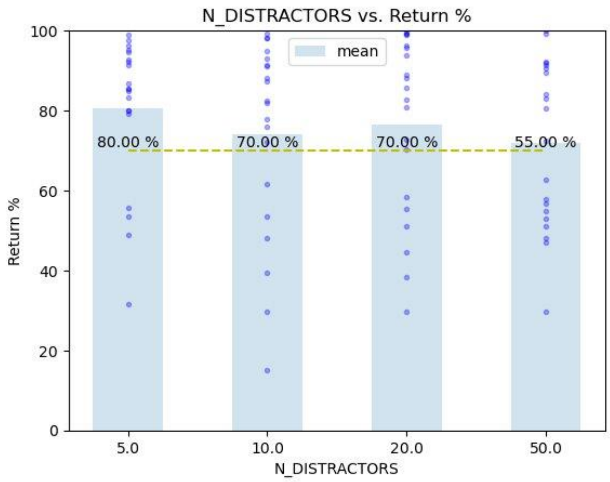

BG_NOISE vs. Return %
20.00 %
75.00 %
80.00 %
75.00 %
60.00 %
Return %
BG_NOISE
mean


RA_NOISE vs. Return %
60.00 %
65.00 %
60.00 %
60.00 %
65.00 %
Return %
RA_NOISE
mean


LEARNING_RATE_HL vs. Return %
0.00 %
65.00 %
55.00 %
45.00 %
45.00 %
Return %
LEARNING_RATE_HL
mean

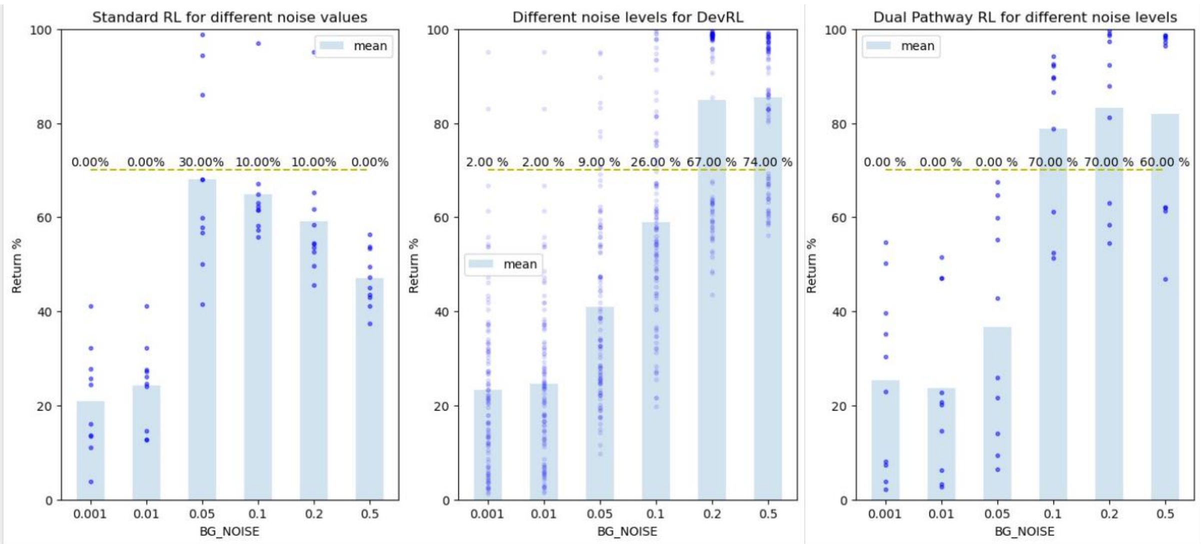

LEARNING_RATE_RL vs. Return %
40.00 %
45.00 %
90.00 %
55.00 %
35.00 %
Return %
LEARNING_RATE_RL
mean

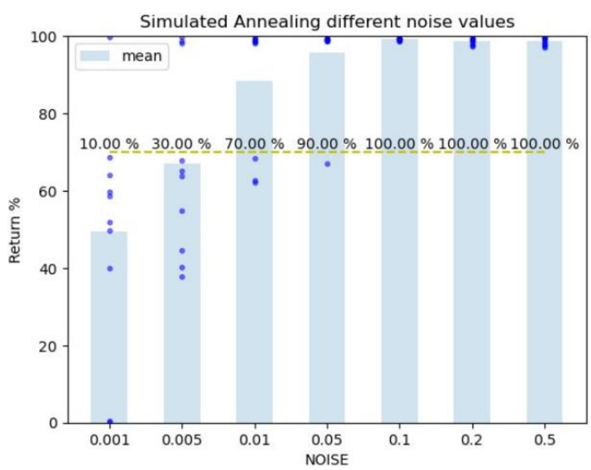


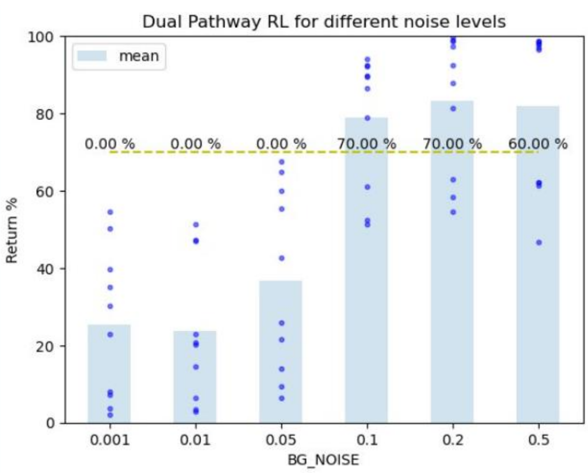


Benchmarks

Here, we compare our model with other algorithms which can solve this 2D reward landscape problem.







Conclusion

We proposed a new algorithmic implementation for efficient sensorimotor learning in the face of uneven performance landscapes with multiple optima, inspired by the large overnight changes experienced by juvenile vocalizations during early phases of learning and the dual pathway architecture of the vocal learning circuitry in songbirds.

References

1. Dual pathway architecture underlying vocal learning in songbirds | bioRxiv
2. C. Tsallis and D. A. Stariolo, “Generalized simulated annealing,” Physica A: Statistical Mechanics and its Applications, vol. **233**, no. 1-2, pp. 395–406, Nov. 1996.
3. S. Derégnaucourt, P. P. Mitra, O. Feher, C. Pytte, and O. Tchernichovski, “How sleep affects the developmental learning of bird song,” Nature, vol. **433**, no. 7027, p. 710–716, Feb 2005.
4. S. W. Bottjer and F. Johnson, “Circuits, hormones, and learning: Vocal behavior in songbirds,” Journal of Neurobiology, vol. **33**, no. 5, pp. 602–618, Nov. 1997.
5. R. J. Williams, “Simple statistical gradient-following algorithms for connectionist reinforcement learning,” Machine Learning, vol. **8**, no. 3-4, pp. 229–256, May 1992.
6. M. Sizemore and D. J. Perkel, “Premotor synaptic plasticity limited to the critical period for song learning,” Proceedings of the National Academy of Sciences, vol. **108**, no. 42, pp. 17 492–17 497, Oct. 2011.
7. V. Gadagkar, P. A. Puzerey, R. Chen, E. Baird-Daniel, A. R. Farhang, and J. H. Goldberg, “Dopamine neurons encode performance error in singing birds,” Science, vol. **354**, no. 6317, pp. 1278–1282, Dec. 2016.

Declaration

1. Declaration by the Scholar:

I Atharv Suryawanshi hereby declare that the details/facts mentioned above are true to the best of my knowledge and I solely be held responsible in case of any discrepancies found in the details mentioned above.

(Signature of Scholar)

Date: 23/08/2024

Place: Bengaluru, 560012