Master Thesis - Computational model of Zebra Finch song learning and the influence of sleep on it

Paul Ecoffet

The 6th of June, 2017

Abstract

The Zebra Finches are songbirds which learn the song of their tutor. They learn it from 25 days post hatch (DPH) to 90 DPH (Liu, Gardner, & Nottebohm, 2004). Zebra finches are commonly used as a model of speech acquisition.

Derégnaucourt, Mitra, Fehér, Pytte, and Tchernichovski (2005) showed that sleep plays an important role in the learning of tutor songs. Indeed, they showed that sleeping has a negative impact on song restitution by zebra finches in the short term but a positive impact on the long run. Song restitution is less complex and less similar to the tutor song from one morning to the previous day evening, but the greater this loss in performance was overall for one bird, the better this bird was able to reproduce the tutor song at the end of its learning.

In addition to that, Dave and Margoliash (2000) have found neurons in the motor cortex which fires sequences during sleep that correspond to their activity pattern when the birds sing in adult zebra finches. This shows that motor neurons that are highly correlated with bird's own song (BOS) are activated during the night. These identified replays suggest that some learning may occur during sleep that use past experiences.

Our hypothesis is that during its sleep, the zebra finch restructures the knowledge it has acquired so far thanks to replay mechanisms. We hypothesize that this restructuring can account for the loss of performance in the short term and an improvement of performance in the long term.

The goal of this internship is to offer a model of the zebra finch song learning which can explain different behavioral data observed such as the correlation between the loss of performance every night and the overall performance at the end of learning.

Contents

1. Introduction

1.1 Zebra finch song learning

The Zebra Finches are songbirds which learn the song of their tutor. They learn it from 25 days post hatch (DPH) to 90 DPH (Liu et al., 2004). Songbird and especially Zebra finches are commonly used as a comparison with human about vocal development. Indeed, the song they produce are not innate even though they have predispositions toward learning their songs. The songs have rather complex structure, with a chaining of syllables that forms a ‘‘motif’’ (Doupe & Kuhl, 1999; Margoliash, 2002).

These common characteristics can be studied easily with Zebra Finch. These birds do learn their song quickly and they produce very stable and reproducible songs. Zebra Finches learn only one song from a tutor and will sing it its whole life. Therefore, the developmental trajectory of this learning can be tracked and evaluation about the quality of the learning can be made.

The neuroanatomy of Zebra Finch has also been studied and the different structures involved in singing has been identified.

Why model of speech acquisition: * fast learning (90 days) * Learning during development Margoliash, 2003 * Very reproducible result with a tutor song that the bird will mimic its whole life Margoliash and Schmidt, 2010 * Close ended learners vs open-ended learner Margoliash and Schmidt, 2010 * Many-to-many relationship between auditory feedback and muscle outputs Margoliash, 2003

* Can be easily raised domestically (Tchernichovski & Margoliash, 2013) * More localized brain structure (Tchernichovski & Margoliash, 2013) * Can study circuitries

The stages of learning * subsong, plastic, crystallization Margoliash and Schmidt, 2010

1.2 Neurobiology

Anatomy of the birdsong brain.

1.3 Sleep

Derégnaucourt et al. (2005) showed that sleep plays an important role in the learning of tutor songs. Indeed, they showed that sleeping has a negative impact on song restitution by zebra finches in the short term but a positive impact on the long run. Song restitution is less complex and less similar to the tutor song from one morning to the previous day evening, but the greater this loss in performance was overall for one bird, the better this bird was able to reproduce the tutor song at the end of its learning.

Dave and Margoliash (2000) have found neurons in the motor cortex which fires sequences during sleep that correspond to their activity pattern when the birds sing in adult zebra finches. This shows that motor neurons that are highly correlated with bird’s own song (BOS) are activated during the night. These identified replays suggest that some learning may occur during sleep that use past experiences.

* Replays can explain learning Margoliash, 2003 * Consolidate learning * Needed to reach new sounds Margoliash, 2003 * replays with weird burst inside Margoliash, 2002

1.4 Gestures model

1.5 Previous models for birdsong learning with Zebra Finches

Even if the neurobiological structures involved in singing have been heavily studied, only a few models of birdsong learning have already been proposed, even less have been implemented.

Reinforcement learning is often evoked as the strategy the birds use to learn their song (Dave & Margoliash, 2000; Marler, 1997). Though, the authors only talk very briefly about reinforcement learning more ref and do not really implement the birdsong learning algorithm with reinforcement learning. They do not explain what would be the state space, the action space and the reward function.

Marler (1997) built a computational model of Zebra Finch birdsong learning. The computational model is based on a sound synthesizer, therefore Coen's algorithm has to deal with real sounds. In his algorithm, the bird learns the sensorimotor map of its vocal production. The bird does random motor movement and group them according to the different characteristics the produced sound has. With enough babbling, the simulated bird is able to reproduce its tutor song. Interesting concepts are brought by Marler's approach. For instance, he brought the concept of ‘‘songemes'', the song equivalent of phonemes. A syllables is composed of several songemes. Indeed, by having to build an algorithm that actually produces songs, the notion of syllables or even notes is not sufficient enough. Syllables and notes are relevant in the sensory space, but not in the motor space. Songemes are described by Coen as the primitive units of bird song. Though, Coen's model has several issues. list issues

* Preference for same species songs Margoliash, 2002; Marler, 1997 * Marler, 1997 * Coen, 2007 with a strange clustering technique

1.6 Sum up

Our hypothesis is that during its sleep, the zebra finch restructures the knowledge it has acquired so far thanks to replay mechanisms. We hypothesize that this restructuring can account for the loss of performance in the short term and an improvement of performance in the long term.

The goal of this internship is first of all to provide a model of the zebra finch song learning with realistic constraints. This model will then allow us to explore different strategies that the bird may use to learn the tutor song. The strategies that we will test would have different prerequisites that could be tested experimentally.

Thanks to this model, we are able to test easily different strategies of learning during the day and during sleep. We are therefore able to look for learning strategies that yield similar results as the observed data. If a combination of strategies yield the correlation between the loss of performance every night and the overall performance at the end of learning, we can hypothesize that zebra finch are using similar learning strategies and we can make new predictions that can be tested experimentally to test the robustness of our model.

2. Our proposed model

2.1 Synthesizer

We want to build a model with realistic constraints, both in the computational budget required by the bird to learn its song as of the actual material the model deals with. We therefore uses a realistic zebra finch song synthesizer. Perl, Arneodo, Amador, Goller, and Mindlin (2011) built a realistic model of the Zebra Finch vocal apparatus. They described with differential equations its behaviour, taking into account parameters such as the length of the syrinx of the bird and are able to reproduce accurately real zebra finches song. The reproduction is good enough to activate bird's own song specific neurons zebra finches have (Boari, Perl, Amador, Margoliash, & Mindlin, 2015). more examples

The synthesizer takes as input a stream of two parameters: The air sac pressure, that is how much air is flowing in the vocal apparatus of the bird, and syringeal labial tension, which is equivalent to the vibration of our vocal . These two values are changed by the muscles in the vocal apparatus of the bird, and we can therefore infer that the motor command sent by the bird brain to the muscles of its vocal apparatus have the purpose of changing these values. find the word

This synthesizer provides a very interesting framework to work with birdsong learning. It constraints a realistic motor space and generates realistic songs in the sensory space. Therefore, our algorithm works on real sounds and have to find parameters that are roughly equivalent to the parameters send by the bird to its muscles.

Our algorithm looks for the best values to parametrize the synthesizer.

2.2 Global architecture

2.2.1 Terminology

Tutor song The tutor song is the goal song the agent try to reproduce.

Song Model A song model is the representation of the motor commands an agent has to produce a song. A song model is composed of several gestures, with the associated parameters and duration.

Song structure The song structure is the agencement of the gestures. Without modifying the parameters of a gesture, the song structure can change by inserting a new gesture, deleting one or changing the length of a gesture.

Gesture A gesture is the motor primitive of the song. A gesture is defined by its duration and motor command generator parameters.

Learning model A learning model is an algorithm that modify Song Models so that they match better the tutor song. A learning model can be used either during "days" or "nights".

2.2.2 Overview

2.2.3 Memorization of the tutor song template

We assumed the tutor song template was already known by the bird and that it has a perfect access to it. This is consistent with results in the literature. Indeed, zebra finches need to listen to the tutor song

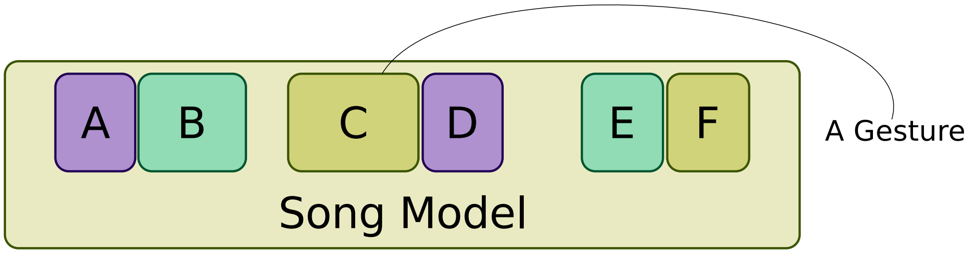

Figure 2.1: Song Architecture

only for a short critical period which occurs a bit before the starting of their babbling, from 20DPH to 50 DPH (Derégnaucourt et al., 2005; Margoliash & Schmidt, 2010). The encoding of the tutor song is a separate event from the vocal imitation. We simplified the tutor representation in our model by a full knowledge of the tutor song characteristics, always accessible by the bird for comparison with its own production.

2.2.4 Song representations

The agent has several song models that he works on. The song models is modified throughout the learning so that the motor commands it describes generate accurately the tutor song.

Song architecture

The song architecture is determined by the number of gestures the song model has, their durations and their starting point. Figure 2.1 shows a simple song architecture.

Gestures

A gesture is determined by its length and the parameters that characterize the generators for Syringeal Labial Tension ($\alpha(t)$) and Air sac Pressure ($\beta(t)$).

$$\alpha(t) = a_\alpha \times t + b_\alpha + \sum_{i=1}^{3} c_{i,\alpha} \sin(\omega_{i,\alpha} \times 2\pi \times t + \phi_{i,\alpha}) + k_\alpha \tag{2.1}$$

$$\beta(t) = a_\alpha \times t + b + c_\beta \sin(\omega_\beta \times 2\pi \times t + \phi_\beta) + k_\beta \tag{2.2}$$

2.2.5 Day learning models

* Default parameters found th
 * hill-climbing * Optimize gesture but not song structure

2.2.6 Night learning models

* Microbial GA * Optimize only song structure, not gestures

2.2.7 Parameters

Fixed parameters Optimized parameters

2.2.8 Satellite Modules

I built several side projects that were needed for the computational model to work.

Bird song analysis package

The research community about birdsong uses a specific set of acoustic features to describe songs. The community use the software Sound Analysis Pro (SAP) 2011 to extract them, or the Matlab equivalent Sound Analysis Toolbox (SAT) (Tchernichovski, Nottebohm, Ho, Pesaran, & Mitra, 2000). SAP2011 is coded in C++ and only compatible with Windows systems. It is also impossible to make calls to its funcion with Python. In the same way, SAT was impossible to call from Python. I have therefore ported the main functions of SAT and SAP to Python 3. I have recoded all the feature extraction functions, the similarity measurement and created plotting functions. I have also done plenty of optimisation to make the code run as fast as possible, because most of the feature extractions are very slow and I had issue with computation time on my project. The source code is available at https://github.com/PaulEcoffet/birdsonganalysis. While I did not get the exact same results as SAT, the results I have with this are qualitatively equivalent. proof read

Synthesizer

I used the synthesizer provided for download at http://www.lsd.df.uba.ar (Boari et al., 2015). The synthesizer was built in C and was not very flexible. I have corrected a few “bugs” in the synthesizer (such as injection of parameters at specific times) and make it integrable with Python and Numpy thanks to Cython. The synthesizer was therefore callable by a Python function. It generates sound waves with a stream of parameters α and β. The source code for this synthesizer is available at https://github.com/PaulEcoffet/birdsynth.

2.3 Run methodology

Grid search on cluster

How to create new models?

3. Results

3.1 Syllables development trajectories

3.2 Influence of song model restructuration on learning

4. Discussion

5. Conclusion

Bibliography

Boari, S., Perl, Y. S., Amador, A., Margoliash, D., & Mindlin, G. B. (2015, November 15). Automatic reconstruction of physiological gestures used in a model of birdsong production. *Journal of Neurophysiology*, *114*(5), 2912–2922. doi:10.1152/jn.00385.2015

Coen, M. H. (2007). Learning to sing like a bird: The self-supervised acquisition of birdsong. In *PROCEEDINGS OF THE NATIONAL CONFERENCE ON ARTIFICIAL INLIGENCE* (Vol. 22, p. 1527). Menlo Park, CA; Cambridge, MA; London; AAAI Press; MIT Press; 1999.

Dave, A. S. & Margoliash, D. (2000, October 27). Song replay during sleep and computational rules for sensorimotor vocal learning. *Science*, *290*(5492), 812–816. doi:10.1126/science.290.5492.812

Derégnaucourt, S., Mitra, P. P., Fehér, O., Pytte, C., & Tchernichovski, O. (2005, February 17). How sleep affects the developmental learning of bird song. *Nature*, *433*(7027), 710–716. doi:10.1038/nature03275

Doupe, A. J. & Kuhl, P. K. (1999). Birdsong and human speech: Common themes and mechanisms. *Annual review of neuroscience*, *22*(1), 567–631.

Liu, W.-c., Gardner, T. J., & Nottebohm, F. (2004). Juvenile zebra finches can use multiple strategies to learn the same song. *Proceedings of the National Academy of Sciences*, *101*(52), 18177–18182.

Margoliash, D. (2002, December 1). Evaluating theories of bird song learning: Implications for future directions. *Journal of Comparative Physiology A: Sensory, Neural, and Behavioral Physiology*, *188*(11), 851–866. doi:10.1007/s00359-002-0351-5

Margoliash, D. (2003, August). Offline learning and the role of autogenous speech: New suggestions from birdsong research. *Speech Communication*, *41*(1), 165–178. doi:10.1016/S0167-6393(02)00101-2

Margoliash, D. & Schmidt, M. F. (2010, October). Sleep, off-line processing, and vocal learning. *Brain and Language*, *115*(1), 45–58. doi:10.1016/j.bandl.2009.09.005

Marler, P. (1997, November). Three models of song learning: Evidence from behavior. *J. Neurobiol.* *33*(5), 501–516.

Perl, Y. S., Arneodo, E. M., Amador, A., Goller, F., & Mindlin, G. B. (2011, November 16). Reconstruction of physiological instructions from zebra finch song. *Physical Review E*, *84*(5). doi:10.1103/PhysRevE.84.051909

Tchernichovski, O. & Margoliash, D. (2013). Time scales of vocal learning in songbirds. In S. A. Helekar (Ed.), *Animal models of speech and language disorders* (pp. 43–60). DOI: 10.1007/978-1-4614-8400-4_3. New York, NY: Springer New York.

Tchernichovski, O., Nottebohm, F., Ho, C. E., Pesaran, B., & Mitra, P. P. (2000, June). A procedure for an automated measurement of song similarity. *Animal Behaviour*, *59*(6), 1167–1176. doi:10.1006/anbe.1999.1416