

Interactions between learning and evolution in simulated avian communication

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Abstract. This paper presents a computational framework for studying the influence of learning on the evolution of avian communication. We conducted computer simulations for exploring the effects of different learning strategies on the evolution of bird song. Experimental results show the genetic assimilation of song repertoires as a consequence of interactions between learning and evolution.

1 Introduction

The evolution of avian communication is an excellent domain for studying fundamental questions of artificial life research. Previous work by Sasahara and Ikegami [14][15], have shown that we are able to explore important issues such as emergence, self-organization and cultural evolution within this framework. Similarly, artificial life models provide a convenient alternative to complex playback and genetic experiments for validating theories of bird song evolution by means of computer simulations.

Bird song studies have been established as instrumental in resolving the debate over instinct versus learning in the ontogeny of behavior [3]. There is a wide variety of patterns in the development of song. For example, among the suboscines normal song develops in individuals that are isolated and or even deafened at an early age. In contrast, among oscines, individuals typically need an external model and intact hearing for normal song development to occur[10]. In addition, birds have been excellent subjects for studying how signals are transmitted and perceived in noisy environments and how the structure of vocalizations can be optimized to achieve these goals [9]. We believe these studies are crucial for understanding the origin and evolution of communication systems with the complexity of human languages.

The aim of this work is to study the effects of learning on the evolution of avian communication using computer simulations. To this end, we formulate a computational framework based on the seminal model proposed by Hinton and Nowlan [8] and further developed by Ackley and Littman [1], among others.

In addition, we explore the effects of a noisy communication channel on the evolution of bird song within the proposed framework. Experimental results show that communicative behaviors become innate as a consequence of interactions between learning and evolution.

2 The model

2.1 Environment

In our model, the environment consists of a population of communicative agents \mathcal{A} . This population represents a simulated bird species. The environment may include other simulated bird species \mathcal{B}_i that sing different songs with respect to \mathcal{A} .

2.2 Agent architecture

In our model, a simulated bird consists of an agent architecture that represents his song repertoire. The formal definition of the agent architecture presented below is based on considerations of the model proposed by Vallejo and Taylor [16].

Agent Let $S = \{s_1, \dots, s_n\}$ be a finite set of n songs and $R = \{r_1, \dots, r_m\}$ be a finite set of m external referents. An *agent* A is a pair (δ, ϕ) , where

1. $\delta : R \rightarrow S \cup \{s_\#\}$ is the transmission function, where $s_\#$ is the undetermined song, and
2. $\phi : S \rightarrow R \cup \{r_\#\}$ is the reception function, where $r_\#$ is the undetermined referent.

Communication An agent $A_1 = (\delta_1, \phi_1)$ communicates to an agent $A_2 = (\delta_2, \phi_2)$ as follows. Initially, A_1 perceives the referent r_i and produces a song s_j according to the mapping described by the transmission function δ_1 , such that $\delta_1(r_i) = s_j$. Once A_1 produces the song s_j , the agent A_2 interprets the song s_j as the referent r_k according to the mapping described by the reception function ϕ_2 , such that $\phi_2(s_j) = r_k$. A communication event from A_1 to A_2 is successful if the following conditions are satisfied:

1. $\delta_1(r_i) = s_j$,
2. $\phi_2(s_j) = r_k$, and
3. $r_i = r_k$

Innate transmission Let $A = (\delta, \phi)$ be an agent. A transmission from A for a given referent r_i is said to be innate if $\delta(r_i) \neq s_\#$ and is said to be subject to learning if $\delta(r_i) = s_\#$.

Innate reception Let $A = (\delta, \phi)$ be an agent. A reception of A for a given song s_j is said to be innate if $\phi(s_j) \neq r_\#$ and is said to be subject to learning if $\phi(s_j) = r_\#$.

Learning In our model, both transmission and reception behaviors of an agent are partially learned. Before a communication event from A_1 to A_2 takes place, A_1 replaces the undetermined songs in δ_1 with songs in S using a predefined learning strategy. Similarly, A_1 replaces the undetermined referents in ϕ_1 with referents in R using the learning strategy. A_2 proceeds similarly.

A fundamental aspect of our model is that learning is performed for communication purposes and does not modify permanently the actual description of an agent. In other words, learned characteristics are not transmitted to offspring during reproduction.

2.3 Learning strategies

We consider two different learning strategies: imitator and improviser, as they are two main forms of bird song learning [7][11]. These strategies are described below.

Imitator An imitator learner replaces the undetermined songs in his transmission function by the corresponding songs in the transmission function of a teacher. Similarly, he replaces the undetermined referents in his reception function by the corresponding referents in the reception function of a teacher.

Formally, a learner $A_1 = (\delta_1, \phi_1)$ imitates a teacher $A_2 = (\delta_2, \phi_2)$ as follows.

1. $\delta_1(r_i)$ is set to $\delta_2(r_i)$ if $\delta_1(r_i) = s_\#$, $\delta_2(r_i) \neq s_\#$, for $i = 1, \dots, n$, and
2. $\phi_1(s_j)$ is set to $\phi_2(s_j)$ if $\phi_1(s_j) = r_\#$, $\phi_2(s_j) \neq r_\#$, for $j = 1, \dots, m$.

Improviser An improviser learner replaces the undetermined songs in his transmission function by random songs in S . Similarly, he replaces the undetermined referents in his reception function by random referents in R .

Formally, a learner $A_1 = (\delta_1, \phi_1)$ improvises as follows.

1. $\delta_1(r_i)$ is set to $random(S)$ if $\delta_1(r_i) = s_\#$, for $i = 1, \dots, n$, and
2. $\phi_1(s_j)$ is set to $random(R)$ if $\phi_1(s_j) = r_\#$, for $j = 1, \dots, m$.

2.4 Evolution of communication

In our model, a population of simulated birds are intended to evolve successful communication at the population level. We use genetic algorithms for this purpose. The design decisions presented below are based on considerations of the performance of genetic algorithms in practical applications [13].

Genome representation An agent $A = (\delta, \phi)$ is represented linearly as follows

$$A = (\delta(r_1), \dots, \delta(r_n), \phi(s_1), \dots, \phi(s_m))$$

Genetic operators Agents produce a new offspring by means of genetic operators. Fitness proportional selection, one-point recombination and point mutation operate on the linear representation of agents described above.

Fitness function Fitness is defined as the communicative accuracy of agents. The communicative accuracy is the ability of an agent to successfully communicate with a collection of other agents.

Let P be a finite population of agents, A be an agent in P , and $Q \subseteq P$ be a non empty collection of agents. The communicative accuracy of A with respect to Q given the set of referents $R = \{r_1, \dots, r_n\}$ and the set of songs $S = \{s_1, \dots, s_m\}$, $C(A, Q, R)$, is defined as

$$C(A, Q, R) = \frac{\sum_{r_i \in R} \sum_{A_k \in Q} c(A, A_k, r_i) + c(A_k, A, r_i)}{|Q|}$$

where $c(A, A_k, r_i) = 1$ if the communication event from A to A_k is successful given the referent r_i , and 0 otherwise; $|Q|$ is the cardinality of Q . $c(A_k, A, r_i)$ is defined similarly.

There is evidence of both temporal song avoidance and song divergence in neighbouring bird species [5][6]. We consider this fact in our model as follows.

If there exist other simulated bird species \mathcal{B}_i in the environment, then a distance component is added to the fitness value defined above. The distance between an agent A and other simulated bird species \mathcal{B} is defined as follows

$$D(A, \mathcal{B}) = \frac{\sum_{\mathcal{B}_i \in \mathcal{B}} H(A, \mathcal{B}_i)}{|\mathcal{B}|}$$

where $H(A, \mathcal{B}_i)$ is the Hamming distance between A and \mathcal{B}_i .

Therefore, the fitness of an agent A is defined as

$$f(A) = C(A, Q, R) + D(A, \mathcal{B})$$

3 Experiments and results

A series of experiments were conducted to investigate whether a population of simulated birds is likely to arrive to successful communication at the population level. In addition, we validated the evolutionary performance of competing learning strategies. Most importantly, we were interested in exploring the effects of learning on the genetic description of an evolving population of simulated birds.

1. Create an initial random population P of agents
2. Do **until** a predefined number generations is met
 - (a) **For each** individual $A_i = (\delta_i, \phi_i) \in P$ **do**
 - i. Perform the learning process of A_i according to the learning strategy with respect to a random agent $A_h \in P$
 - ii. Select a random subpopulation of agents $Q \subseteq P$
 - iii. Perform the learning process for all $A_j \in Q$ according to the learning strategy of A_j with respect to a random agent $A_k \in P$
 - iv. Measure the communicative accuracy of A_i with respect to Q , $C(A_i, Q, R)$, given the set of referents R
 - v. Measure the distance of A_i with respect to \mathcal{B} , $D(A_i, \mathcal{B})$, for all extant species \mathcal{B}_i
 - vi. Compute the fitness $f(A_i) = C(A_i, Q, R) + D(A_i, \mathcal{B})$
 - End for**
 - (b) Select two individuals $A_{mother} \in P$ and $A_{father} \in P$ for reproduction using fitness proportional selection
 - (c) Produce an offspring A_{new} from A_{mother} and A_{father} using one-point recombination and point mutation
 - (d) Select a random individual $A_{old} \in P$
 - (e) Replace A_{old} by A_{new}
- End do**

Table 1. Simulation procedure

Finally, we explore the influence of different levels of noise in the communication channel on the genetic assimilation of traits. The simulation procedure is described in table 1.

Extensive simulations were conducted using different combinations of parameter values as shown in table 2. The following were the major results:

1. In one-strategy simulations, imitators arrived to highly accurate communication at the population level. On the other hand, improvisers reached local maxima in communication accuracy consistently. Figure 1 shows the results of representative simulations of the two learning strategies.
2. In one-strategy simulations, imitation produced the genetic assimilation of both songs and referents. On the other hand, improvisation reduced the undetermined songs and referents but they were not totally assimilated. Figure 2 and figure 3 show the frequency of undetermined songs and undetermined referents in the population of the two learning strategies, respectively.
3. In two-strategy simulations, a population of imitators dominated a population of improvisers. In most cases, imitators took over the entire population. Very rarely, a few improvisers prevailed in the population. Figure 4 shows the frequency of strategies in the population of a typical two-strategy simulation.
4. In one-strategy simulations when there were other species present in the environment, a densely populated environment produced a faster genetic assimilation of both songs and referentes. Figures 5 and 6 show the frequency of

Parameter	Value
undetermined traits	50%
generations	3000
population P	256
subpopulation Q	16
songs S	4-8
referents R	4-8
crossover probability P_c	0.6
mutation probability P_m	0.001
species \mathcal{B}	0-32

Table 2. Parameters for simulations

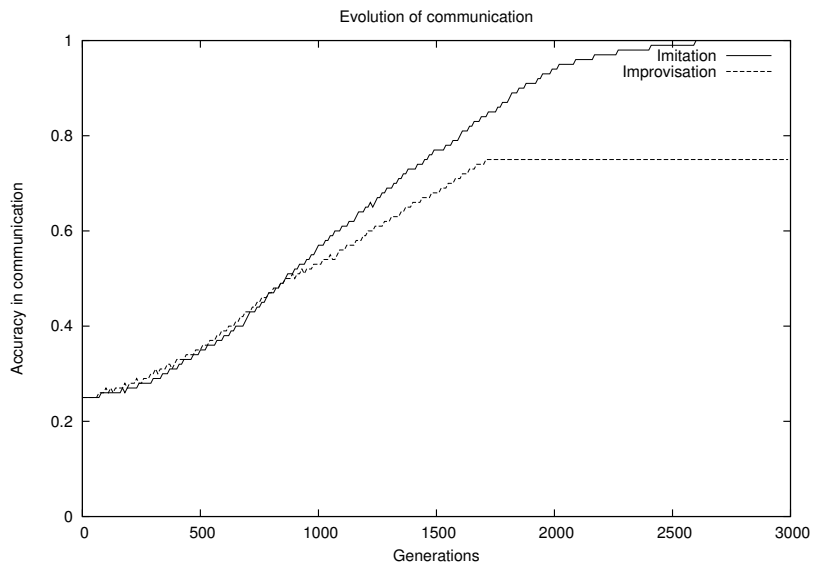


Fig. 1. Evolution of communication in one-strategy simulations

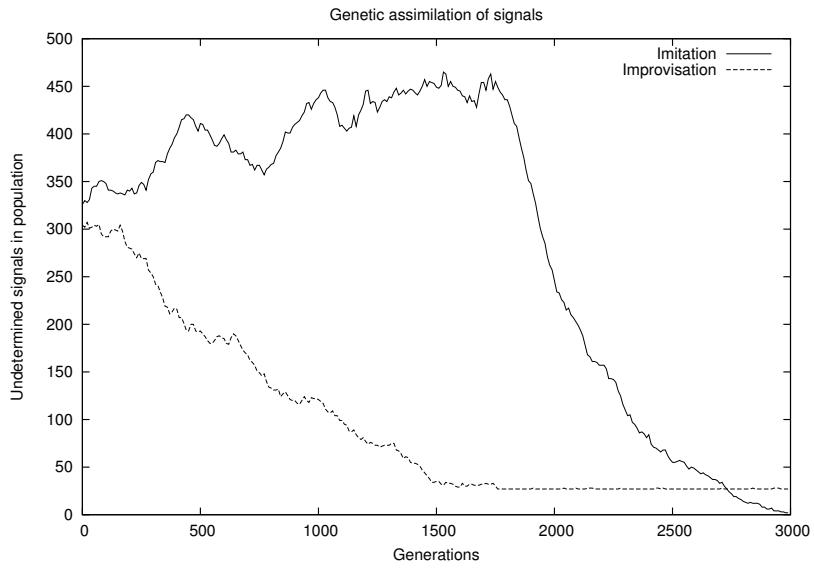


Fig. 2. Genetic assimilation of songs in one-strategy simulations

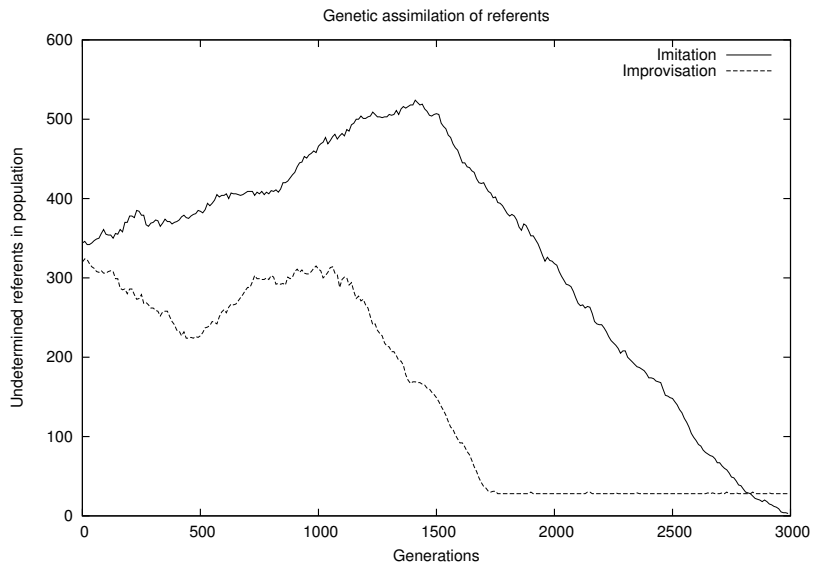


Fig. 3. Genetic assimilation of referents in one-strategy simulations

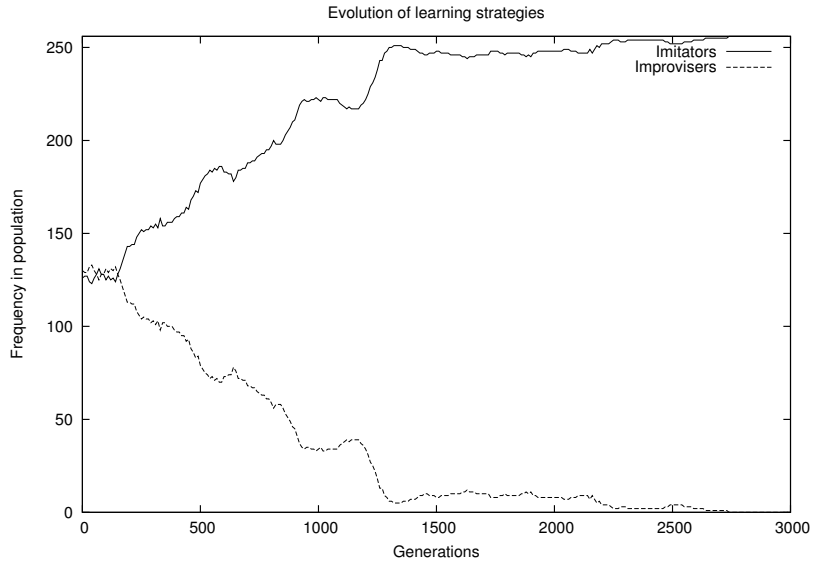


Fig. 4. Frequency of learning strategies in two-strategy simulations

undetermined songs and undetermined referents in the population of a characteristic two-strategy simulation with different number of species present in the environment, respectively.

4 Discussion

Overall, experimental results indicate that a population of agents is capable of arriving to highly successful communication. Both transmission and reception behaviors became innate as a consequence of the interaction between learning and evolution.

Why communicative behaviors became innate? First, imitation of conspecifics in a static environment provides the opportunity for the genetic assimilation of transmission and reception behaviors. Second, the competition for the communication channel contributes to accelerate the assimilation of traits. There are examples of similar innate underpinnings in bird song [12].

So far, we have not considered the cost of producing a song. The fundamental issue of honesty would arise as a result of this consideration. Previous artificial life studies have provide insights on this topic [2].

We believe that the proposed framework could also be used for testing theories on allopatric speciation, song sharing, stability of song types [4]. These studies would contribute to elucidate the origins and evolution of bird song.

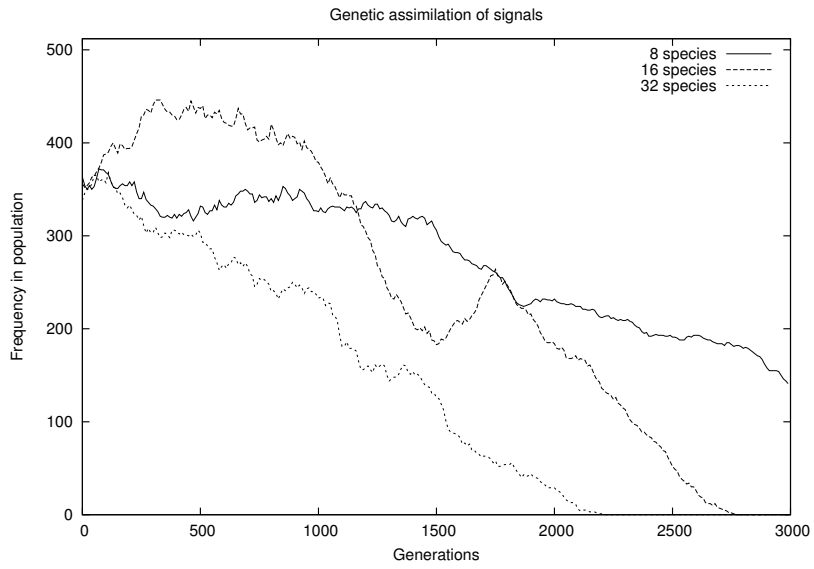


Fig. 5. Genetic assimilation of songs in noisy environment

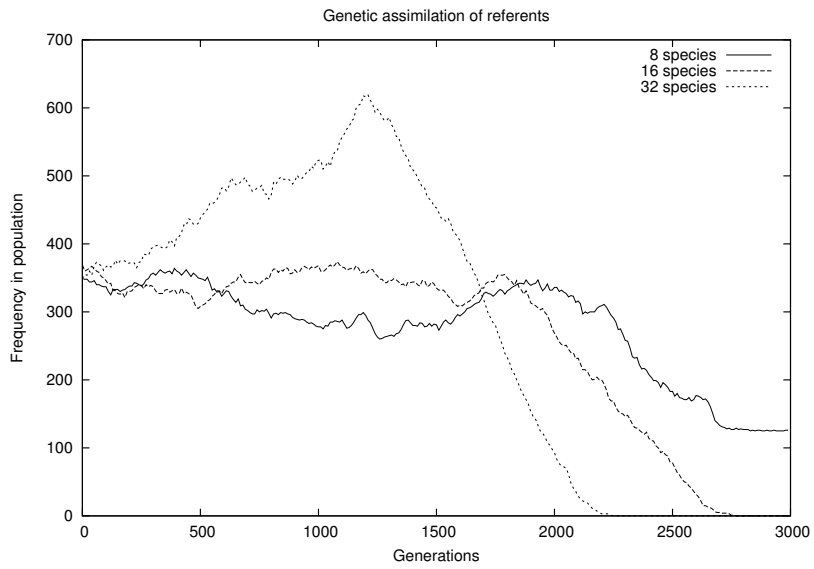


Fig. 6. Genetic assimilation of referents in noisy environment

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