

# Birdsong Acquisition Model by Sexual Selection Focused on Habitat Density

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**Abstract.** We describe a simulation model based on an avian ecosystem for determining what causes birdsong evolution. It is already known that songbirds communicate with a “birdsong.” This birdsong is used in territorial and courtship behaviors. Some previous researches have suggested that songs related to territorial behaviors should have simple structures while those related to courtship behaviors should have complex ones. We suspect that birdsongs are constantly evolving to achieve a suitable balance between the two behaviors while considering the surrounding environment. We consider avian habitat density to be one of the most important environmental factors influencing birdsong evolution and therefore created different densities in a simulation model. In this paper, we propose a birdsong acquisition model by sexual selection that contains both territorial and courtship behaviors. We conducted simulations with the proposed model and determined that the evolution of birdsongs differs depending on a bird’s habitat density.

**Keywords:** Artificial Life, Sexual Selection, Birdsong, Evolutionary Simulation.

## 1 Introduction

Songbirds that belong to the passerine order communicate with each other using their voices. Bird vocalizations include both birdsongs and calls; birdsongs are acquired after birth and sung by only the male birds while calls are inherent. Songs are long and complex and are associated with territorial and courtship behaviours, while the shorter calls tend to functions as simple signals or alarms. In this paper, we focus on the songs. It is currently thought that the territorial and courtship behaviours affect sexual selection for the following reasons [4].

- Songbirds’ territorial behaviour

The male birds display territorial behaviour by singing songs. Those that sing short, simple, and stereotyped songs have an advantage in that they can be easily recognized by their neighbors. It is assumed that the effect is one of the results of Dear Enemy Effect that reduces aggressiveness to neighbors for the energy saving [3].

– Songbirds’ courtship behaviour

The female birds hear the songs of the male birds and use them to search for and select their mates. They tend to prefer longer and more complex songs, which is non-adaptive to survival and caused by the handicap principle [1].

The birds sing different songs according to their habitat — like dialects, even if they are closely related species — and observers expect that the songs evolve to achieve a more suitable balance of the two behaviors depending on the surrounding environment [6]. However, it is difficult to confirm this expectation due to the necessity of long-term experimentation.

Using an artificially designed computational model to simulate real life is one technique for studying systems related to life [2]. The rapid evolution of software agents makes it possible to simulate challenging experiments like evolution observations [8]. There have been previous studies that use the ecological model for birdsongs [5], and birdsongs can be effectively described with a finite-state grammar. Sasahara and Ikegami have suggested a model in which the grammar of the songs sung by male birds and the grammar of the songs preferred by female birds are expressed as automatons, and they also showed that the courtship behaviour requires birdsongs to have complex structure [10]. However, their model did not deal with the territorial behaviour of birds because they were examining the Bengalese finch, which is a domesticated species. Ritchie and Kirby suggested a model in which the hearing function of birds is expressed as filters [9]. They showed that the territorial behaviour causes the hearing function of a bird to prefer a certain type of song. However, their model did not deal with the courtship behaviour of birds.

In this paper, we describe an evolutionary model of birdsongs that draws on both the Sasahara and Ikegami’s model and Ritchie and Kirby’s model. We express the grammar of the songs as automatons and hearing functions of the birds as filters. The model includes a song pool environment for sharing songs with bird agents in order to design the territorial and courtship behaviour in the avian ecosystem. In addition, we focus on habitat density as one of the key factor of song evolution. We conducted simulations with the proposed model and determined that the evolution of birdsongs differs depending on the habitat density.

## 2 Conventional Model

In this section, we describe the parts of the other two models we adapted to our own model.

### 2.1 Sasahara and Ikegami’s Model

Recent analysis of birdsongs has shown that the songs consist of a regular order of syllables. Therefore, a song  $s_x$  can be defined as

$$s_x = ch_0ch_1..ch_y..ch_{z-1} \quad (ch_i \in \{\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}, \mathbf{e}\}), \quad (1)$$

**Table 1.** Example of a Filter for Recognizing Conspecific Songs

	<b>a</b>	<b>b</b>	<b>c</b>	<b>d</b>	<b>e</b>	<b>E</b>
<b>S</b>	0.08	0.15	0.52	0.07	0.08	0.10
<b>a</b>	0.05	0.84	0.00	0.00	0.05	0.06
<b>b</b>	0.05	0.10	0.18	0.45	0.22	0.00
<b>c</b>	0.82	0.09	0.00	0.09	0.00	0.00
<b>d</b>	0.22	0.30	0.00	0.08	0.00	0.40
<b>e</b>	0.12	0.00	0.30	0.30	0.05	0.23

where  $ch_i$  is the syllable (“chunk”) that is expressed by characters from ‘a’ to ‘e,’ and  $z$  is the number of chunks composing a song  $s_x$ .

It is expressed by individual automaton for the grammar of the songs sung by the agents of male birds and the grammar of the songs preferred by the agents of female birds. In other words, the male bird agents sing a song in accordance with the grammar, and the female bird agents prefer the song in accordance with the grammar. The male agents court the female agents by generating their songs with an automaton for song expression, and the female agents select their mates by valuing songs with an automaton for song preference.

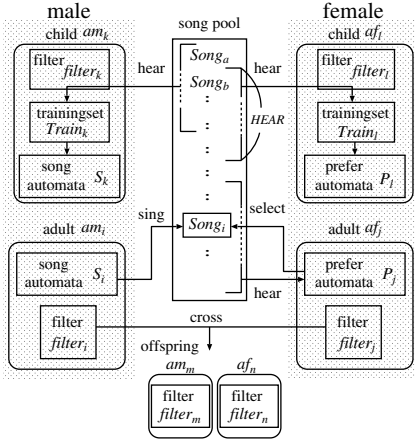
As mentioned earlier, Sasahara and Ikegami’s model does not deal with territorial behaviour because the bird they modeled, the Bengalese finch, is a domesticated species. Their model also does not deal with song learning which is an important factor for the avian ecosystem. It is therefore necessary to add territorial behaviour and song learning structures to their model to design a general evolution model.

## 2.2 Ritchie and Kirby’s Model

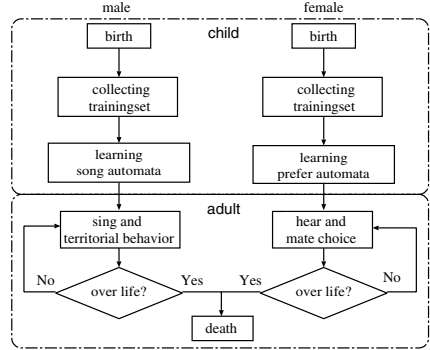
Songbirds that are not born with the ability to sing learn their songs from songs they hear in childhood. They memorize songs they select by a unique hearing function that determines whether the song is conspecific or not. The male birds generate their template of song expression and the female birds generate their template of song preference [7]. Ritchie and Kirby suggested that the hearing function is expressed by filter: conspecific songs are easily memorized through the hearing function, while another species’ songs are difficult to memorize because the hearing function blocks them. The filter is a table consisting of the transition probability from chunk to chunk; an example is shown in Table 1. **S** indicates the start of the song and **E** indicates the end. **a**, **b**, **c**, **d**, **e** indicate individual chunks.

A preference  $prefer(filter_i, s_x)$ , which expresses if a song  $s_x$  is conspecific for filter  $filter_i$ , is defined as

$$prefer(filter_i, s_x) = \frac{\sum_{y=0}^n ft_i(t_y)}{n}, \quad (2)$$



**Fig. 1.** Configuration diagram of the proposed model



**Fig. 2.** A flowchart of agent's life cycle

where  $n$  is the number of chunk transitions in a song  $s_x$  and  $ft_i(t_y)$  is the function that refers to the probability  $t_y$  of the  $y$ th chunk transition of the song  $s_x$  in the  $filter_i$ . A preference  $prefer(filter_i, s_x)$  depends on the selection of training songs and the evaluation of territorial behaviour. It is necessary that Ritchie and Kirby's model be adapted to include the function of courtship behaviour for a general evolutionary model.

### 3 Composition of Computational Model

Our model includes agents as songbirds, song sets as the song repertoire of a songbird, and a song pool as an environment in which to share songs. The configuration diagram of our model — agents, song set, and song pool — is shown in Fig. 1.

A male agent  $am_k$  and a female agent  $af_l$  in childhood refer to the song set  $Song$  in the song pool  $Song\ pool$ , and each generate either a song expression automaton  $S_k$  or song preference automaton  $P_l$  from their training song set acquired through their filter. A male agent in adulthood  $am_i$  stores its song set  $Song_i$ , which consists of its songs sung by song expression automaton  $S_i$ , into the song pool  $Song\ pool$ , while a female agent in adulthood  $af_j$  selects its mate by evaluating some song sets  $Song$  in the song pool  $Song\ pool$  by its song preference automaton  $P_j$ . Details of each definition are shown below.

#### 3.1 Agent

A male agent  $am_i$  and a female agent  $af_j$  ( $i, j$  is the identifier) are expressed by

$$am_i(filter_i, Train_i, sa_i, risk_i) \tag{3}$$

$$af_j(filter_j, Train_j, pa_j), \tag{4}$$

where  $filter_i, filter_j$  is the filter meaning inherent to the hearing function,  $Train_i, Train_j$  is the training song set for song learning,  $sa_i$  is the song expression automaton for generating songs,  $pa_j$  is the song preference automaton for evaluating songs, and  $risk_i$  is the expectation value of risk due to territorial behaviour with other agents. The agent's actions — song learning, territorial behaviour, and courtship behaviour — are described in detail later.

### 3.2 Song Set

A song set  $Song_i$  which is the set of songs generated by a male agent  $am_i$ , is defined as

$$Song_i = \{s_x | x = 1 \dots SONG\}, \quad (5)$$

where  $SONG$  is the number of songs that a male generates.

### 3.3 Song Pool

The song pool, which is a multiset of song sets, is updated each simulation step (approximating one year each). All song sets generated by male agents are stored in the song pool and referred to by other agents. The song pool is defined as

$$Song\ pool = \{Song_i | i = 1 \dots AM\}, \quad (6)$$

where  $AM$  is the number of male agents.

### 3.4 Habitat Density

Habitat density is the population density of all birds in a given area. We believe that habitat density depends on the number of birds that are around a particular bird, in other words, the high habitat density makes birds hear many other songs. In our model, we define  $HEAR$  as the number of song sets referred to by an agent in one step for the purpose of expressing habitat density.

## 4 The Life Cycle of an Agent

The life cycle flowchart of each agent is shown in Fig. 2. An agent's life consists of a childhood phase and an adulthood phase. In childhood, each agent learns songs and in adulthood, male agents generate their songs and calculate the risk of territorial behaviour, while female agents evaluate the male agent's song sets and select their mates. When an agent reaches the end of its lifetime, it dies.

### 4.1 Agent in Childhood

In songbirds ecology, it is known that songbirds make the mold of song after hearing it from some male birds through their inherent hearing function. In our model, an agent collects songs from the song pool through the filter, which is

an inherent component, and generates the song expression or song preference automaton from the collected songs. An agent hears *HEAR* agents' song sets that are randomly selected in the song pool and calculate each of the song's preference through the filter. The training songs we used included five songs that were preferred by the filter.

Next, an agent generates a song expression or song preference automaton from the training songs with the minimum description length (MDL) algorithm. This algorithm, which is a compression algorithm for automatons based on the minimum description length principle, is generally used as a model of language acquisition [11]. Any training songs are accepted by the acquired automaton, and an agent thus develops into adulthood after it finishes learning the songs.

## 4.2 Male Agent in Adulthood

A male agent in adulthood generates a song set that is the set of *SONG* songs accepted by its song expression automaton. However, it is stochastically difficult to generate songs that have a low preference calculated with the filter. Next, the potential risk of territorial behaviour of each male agent is calculated (NOTE: for real songbirds it is better that they memorize simple and recognizable songs to reduce the risk of territorial behaviour). In our model, the risk is calculated by song complexity and song recognition relations with among other agents. A risk  $risk_i$  of male agent  $am_i$  is defined as

$$risk_i = \frac{1}{2} \left( HEAR \cdot complex(Song_i) + \sum_{j=0}^{HEAR} cognit(am_i, am_j) \right), \quad (7)$$

where  $complex(Song_i)$  is the complexity of songs in the song set  $Song_i$  and  $cognit(am_i, am_j)$  is the song recognition relations between  $am_i$  and  $am_j$ . It is apparent that the higher the value *HEAR* expressing habitat density has, the higher value  $risk_i$  has. The details of  $complex(Song_i)$  are shown as

$$complex(Song_i) = \frac{\sum_{s_x \in Song_i} complex\_s(s_x)}{SONG}, \quad (8)$$

$$complex\_s(s_x) = \frac{1}{2} \left( \frac{cht(s_x)}{L\_MAX} + \frac{ch(s_x)}{CHUNK} \right), \quad (9)$$

where  $complex\_s(s_x)$  is the complexity of song  $s_x$  in the song set  $Song_i$ ,  $cht(s_y)$  and  $ch(s_y)$  is the number of chunk transition patterns and the number of chunk types included in song  $s_y$  respectively, *L\_MAX* and *CHUNK* is the maximum number of chunk transitions patterns and the maximum number of chunk types our model allows respectively.

$cognit(am_i, am_j)$  is calculated by

$$cognit(am_i, am_j) = 1 - \frac{1}{2} \left( ps(filter_i, Song_j) + ps(filter_j, Song_i) \right), \quad (10)$$

where  $ps(filter_i, Song_j)$  is the average of  $prefer(filter_i, s_x)$  among  $s_x$  in the  $Song_j$ , defined as

$$ps(filter_i, Song_j) = \frac{\sum_{s_x \in Song_j} prefer(filter_i, s_x)}{SONG}. \tag{11}$$

### 4.3 Female Agent in Adulthood

A female agent in adulthood evaluates song sets in the song pool by a song preference automaton to select its mate (NOTE: real songbirds, the female birds prefer more complex songs learned in their childhood, and they consider territorial quality [7]). The value of these multiple cues is defined and a female agent hear *HEAR* potential mates' song sets that are randomly selected in the song pool. The male agent that is given the highest value is selected as the female agent's mate.  $value(af_j, am_i)$ , which is a female agent  $af_j$ 's assessment of a male agent  $am_i$ , is defined as

$$value(af_j, am_i) = \alpha \cdot sc\_s(pa_j, Song_i) + (1 - \alpha) sc\_t(risk_i), \tag{12}$$

where  $sc\_s(pa_j, Song_i)$  is the score of the song,  $sc\_t(risk_i)$  is the score of the territorial behaviour, and  $\alpha$  is the invariable to normalize these scores, resulting in  $alpha = 0.9$  in our experiment.

$sc\_s(pa_j, Song_i)$ , which consists of the song complexity and acceptability of the song set, is defined as

$$sc\_s(pa_j, Song_i) = complex(Song_i) + \frac{\sum_{s_x \in Song_i} accept(pa_j, s_x)}{SONG}, \tag{13}$$

where  $accept(pa_j, s_x)$  is results in an output 1 if the song  $s_x$  can be accepted by song preference automaton  $pa_j$ . If it cannot, the output is 0.

$sc\_t(risk_i)$ , which is the difference between  $ave\_risk$  (the average of all male agent's risks) and  $risk_i$  (a male agent  $am_i$ 's risk) , is define as

$$sc\_t(risk_i) = ave\_risk - risk_i. \tag{14}$$

A female agent  $af_j$  selecting its mate  $am_i$  generates the next generation  $am_n, af_o$ , whose filters  $filter_n, filter_o$  are given to operate both  $am_i$ 's filter and  $af_j$ 's filter genetically. Agents of the next generation  $am_n, af_o$  are defined as

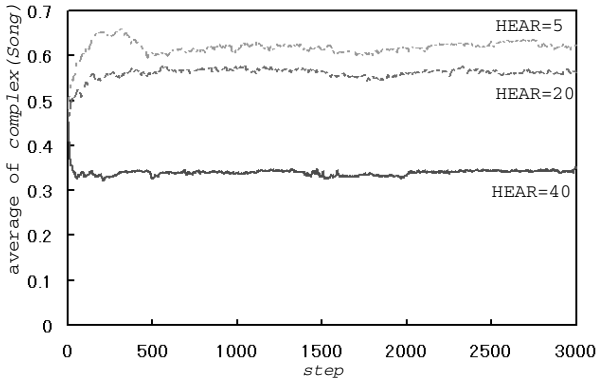
$$am_n(filter_n, \emptyset, \emptyset, \emptyset), \tag{15}$$

$$af_o(filter_o, \emptyset, \emptyset). \tag{16}$$

The next generations are exposed to the selection pressure by roulette-wheel, in which their fitness depends on the value of their parents' value  $value(af_j, am_i)$ . The *AM* male agents and the *AF* female agents in next generation survive, and the others are remove out.

**Table 2.** Simulation Condition

Description	Value
Number of songs which bird hears: <i>HEAR</i>	5, 20, 40
Number of step in simulation	3000
Number of male agent: <i>AM</i>	100
Number of female agent: <i>AF</i>	100
Number of an agent's song: <i>SONG</i>	5
Maximum length of song: <i>L_MAX</i>	10
Kind number of chunk: <i>CHUNK</i>	5
Number of step in agent life-time: <i>LIFE</i>	2

**Fig. 3.** Average values of  $complex(Song)$  in simulations at each *HEAR*

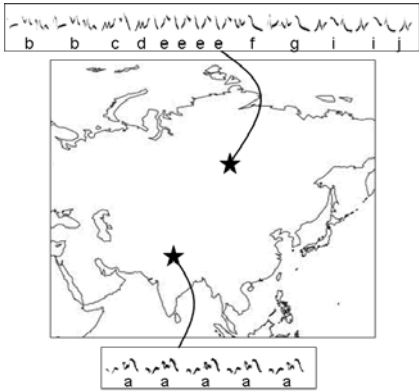
## 5 Simulation and Discussion

We conducted a simulation using our model under the conditions listed in Table 2. Our particular focus was on the influence of avian habitat density on song evolution. As described in section 3.4, avian habitat density is expressed as the number of song sets referred to by an agent in one step *HEAR*. We changed the value of *HEAR* with 5, 20, and 40 to examine the agent's song complexity  $complex(Song)$  acquired by evolution.

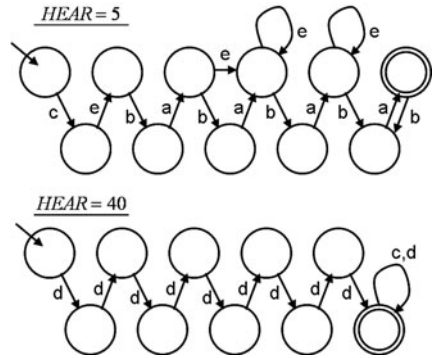
### 5.1 Results

Fig. 3 shows the process of the mean value of  $complex(Song)$  in each value of *HEAR*. The value of  $complex(Song)$  is lower as the value of *HEAR* is higher. In other words, simple songs are acquired when the agents are closely spaced, and the complex songs are acquired when the agents are sparse. We conclude that agents change the weight of their behaviour (territory or courtship) depending on the habitat. From equation (7), the force to reduce the value of  $risk_i$  arises if the value of *HEAR* is higher because of the range expansion in the value of  $risk_i$ .





**Fig. 4.** Example of Greenish Warbler’s song



**Fig. 5.** Example of the agent automaton in the simulation of  $HEAR = 5$ ,  $HEAR = 40$

**Table 3.** Relation Between Habitat Density and Song

habitat density	priority behavior	song complexity
low	courtship	complex
high	territorial	simple

## 5.2 Comparison to the Greenish Warbler

The Greenish Warbler (*Phylloscopus trochiloides*) inhabits forests in much of northern and central Asia, and their songs differ depending on the habitat. Fig. 4 shows the example of Greenish Warbler songs in two different habitats [6]. The songs obtained at the mark on the map are expressed by spectrogram and labeled by the characters of each chunk. The Greenish Warbler in north Asia sings a long complex song, while the one in central Asia sings a stereotyped simple song. It has been theorized that the Greenish Warbler in north Asia acquired complex songs because of the priority given to courtship behaviour based on lower habitat density [6]. The relationship between habitat density and song complexity is shown in Table 3.

Fig. 5 shows examples of automaton obtained in the simulation experiments of  $HEAR = 5$  and  $HEAR = 40$ . The automaton in  $HEAR = 5$  can output songs consisting of more complex chunk transitions than the automaton in  $HEAR = 40$ . Compared to the songs of the Greenish Warbler shown in Fig. 4, there are similar relations between song complexity and some difference between song length. We therefore conclude that the song complexity of birds depends on the avian habitat density.

## 6 Conclusion

In this paper, we examined how a songbird's song evolves due to sexual selection with a focus on habitat density. We conducted an artificial life, multi-agent simulation and determined that the relation between habitat density and song complexity depends on the balance between courtship and territorial behaviours. Bird agents equipped with an inherent hearing function acquired song expression and song preference automata and then communicated with songs. Influenced by the habitat density, which is the number of other birds in the environment, the agents engaged in territorial and courtship behaviour and song learning. When we changed the habitat density, a higher density made the agent's songs simpler and a lower density made them more complex. The simulation was similar to real ecology in terms of the relation between habitat density and song complexity. Though it is necessary to mention whether the more data is the same as those in real ecology, they are hard to be justified. Our future work will focus on the justification of the proposed model.

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