The song structure and repertoire size of Daurian Redstarts (Phoenicurus auroreus) in South Korea

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Abstract: The song repertoire across avian species varies considerably in size, and reliable measurement is important in defining its significance as a target in sexual selection. In this study, the song structure and song repertoire size of the Daurian Redstart (Phoenicurus auroreus) in South Korea were investigated. The songs had major syllable variation rather than song type variation. The average song repertoire size from 20 males was 39.9 ± 5.8 (range: 28–50), based on a syllable type that was appropriate for this species. The songs were structured with three distinguishable parts, where song syllables varied most in the syllable part, and new syllable additions were relatively limited in the whistle and subsyllable parts. Furthermore, new syllables were gradually reduced with an increasing number of males, potentially due to the existence of core syllables in the songs. Our results suggest an individual identity cue may exist in the syllable part of the song and that the less variable whistles within and between individuals may play a role in forming a local dialect. Thus, further research on syllable similarity is needed to find song variations among individuals over greater geographic distances.

Key words: Individual identity, Phoenicurus auroreus, song repertoire size, song structure, syllable type

Songbird songs vary enormously in structure and usage, both across species and among individuals. The songs consist of various structural units (i.e. element, syllable, and phrase), which play a role in identifying an individual (as well as its sex and species) and in communicating with social members (O’Loghlen and Beecher, 1997; Olendorf et al., 2004). In particular, the song shows sexually dimorphic characteristics, as it is mainly used by males in temperate regions in both male–male competition and in female choice. Thus, the song is a primary target of sexual selection that appears as a form of vocal ornament for singing males (Catchpole et al., 1985; Searcy, 1996; Gil and Slater, 2000). Decades of birdsong research have shown that a song or syllable type (called “song repertoire”) of increasing complexity is more efficient in attracting females and excluding intruders from territory (Searcy and Andersson, 1986; Catchpole and Slater, 1995). In addition, the song repertoire size predicts male quality in terms of the size of brain nuclei (McGregor et al., 1981; Székely et al., 1996).

Two methods have been used to measure the song repertoire size. The first classifies the number of song types with distinct and stereotyped structures by unique sequences. Many passerine species have been reported to range from one to several hundred song types: the White-crowned Sparrow (Zonotrichia leucophrys) has only 1 basic type (Marler, 1970), the Song Sparrow (Melospiza melodia) has 6 to 10, and the Rock Wren (Salpinctes obsoletus) has 85 to 90 (Kroodsma, 1982). The sequencing organization of the song types is unique to each species. The second method classifies the number of syllable types by sample size, such as species with unstereotyped song types: the Great Reed Warbler (Acrocephalus arundinaceus), the Sedge Warbler (Acrocephalus schoenobaenus), and the Willow Warbler (Phylloscopus trochilus). Here songs consisted of unsequenced or rarely repeated syllables from the syllable type pool (Catchpole, 1976, 1986; Read and Weary, 1992; Gil and Slater, 2000; Gill and Gahr, 2002). Syllable sharing in songs was a major consideration when determining the size of the song repertoire with syllable types.

The Daurian Redstart (Phoenicurus auroreus, family Muscicapidae) is a small, sexually dimorphic passerine bird. They are common residents in South Korea and are widely distributed across North Asia, including China, Japan, Mongolia, and Central Asian Russia. Their songs are composed of a variable series of short, sweet, mostly descending phrases typically starting with 1–2 short clear
notes followed by a scratchy trill and a wheezy jingling flourish, with some clear, slurred notes (del Hoyo et al., 2016). A recent study on song structure and function by Huang et al. (2012) showed that the songs of Daurian Redstarts were separated into 2 parts: a stereotyped part and a variable part. The authors suggested that the stereotyped part plays a role in identifying individuals, as syllable variations were higher between individuals than within the songs of a single individual. However, to date, the size and variation of the song repertoire of Daurian Redstarts are unknown.

In this study, the song structure and repertoire size of the Daurian Redstart in South Korea were estimated. Song types are immediately repeated in succession with added or deleted syllables, or the song type itself is changed repeatedly. This singing activity makes it difficult to measure the size of the repertoire. Thus, the second method described above was used to estimate the size of the syllable repertoire. This study provides basic information on the variation of song structural features, particularly syllable and syllable types, and examines the variety of the syllable pool, testing hypotheses about song learning processes as units of cultural traits within and among populations. This is the first documentation and analysis of Daurian Redstart songs and their repertoires in South Korea.

The Daurian Redstart's songs were recorded during breeding seasons in 2015 and 2016 in 5 areas of South Korea: the Youngseo districts (Area A), Youngdong districts (Area B), Chungcheong area (Area C), North Gyeongsang area (Area D), and Jeolla area (Area E; Figure 1). Recordings were made (each 10 min in length per male) in the morning between 30 min before sunrise and 1130 hours and in the afternoon between 1500 hours and sunset. Recordings were made using a Marantz PMD660 digital recorder (Marantz, Kawasaki, Japan) with a Telinga Pro 8 DAT parabolic microphone (Telinga, Uppsala, Sweden).

The Daurian Redstart song was divided into three parts based on the song structure: a whistle, a subsyllable, and a syllable (Figure 2). The whistle part consists of several notes with consistent frequency ranges and simple forms, which correspond to the stereotyped part described by Huang et al. (2012). The whistle part is followed by a subsyllable part, which is composed of a brief and limited number of syllable types. The syllable part is the most complex with various types of notes of various frequency ranges and durations. The syllable was used as a unit of song composition to estimate repertoire size. Syllable types were first recognized by inspection based on their morphological, temporal, and frequency distinctiveness; this was confirmed by blind classification by other individuals. Similar syllable types were grouped and labeled with a unique alphanumericic combination to create a syllable catalogue (Figure S1). The catalog has been revised three times after evaluation by independent observers who were not familiar with birdsong. Songs were analyzed using Raven Pro 1.5 (Cornell Laboratory of Ornithology, 2010), with an FFT size of 512 and a contrast value of 84 points.

To estimate the entire syllable repertoire size of males' songs, the cumulative number of syllable types was plotted as a function of the nth song sampled for each male. For this, we selected 20 high-quality songs per male and analyzed a total of 400 songs of 20 males from the 5 study areas. Saturation curves of the cumulative number of syllable types were also plotted as a function of the nth male sampled to estimate the number of syllable types in the syllable pool. In addition, the cumulative number of syllable types was compared in each song part against the nth male sampled in South Korea.

Daurian Redstart songs comprised 1 type of whistle and subsyllable with 2 to 8 syllable types (average: 5.42 ± 1.62) per song. Males sometimes skipped the whistle and subsyllable parts of a song, and the song syllables were not repeated with the same sequence every time. A total of 14 types (types I to XIV) of whistle, 26 types (types a to z) of subsyllable, and 80 types (types 1 to 80) of syllable were found in 400 songs from 20 males (Figure S1).

The cumulative number of syllable types of Daurian Redstart song was plotted against the nth song recorded from 20 individuals (Figure 3). On average, the syllable repertoire size of Daurian Redstarts was 39.9 ± 5.8 per male (range: 28–50). The number of song syllables increased as the song progressed, reaching a maximum number of repertoires by the 18.2th song (average) for 20 males, where the number of song syllable types detected by the 18th song was 97.6% (average) of the total syllable types per male (Table). Furthermore, the cumulative number of syllable types, plotted as a function of the nth bird sampled, defined the entire repertoire of syllables in the Daurian Redstart songs (Figure 4), where the plot showed an S-shaped curve that reached an asymptotic value of 95 types from 20 males.

To examine the structural features of syllable types and usage in each part of a song, the cumulative number of syllables was plotted in each part as a function of the nth bird sampled (Figure 5). The graph slowly increased in whistle and subsyllable parts, where the whistle part showed 7 types in all songs (becoming asymptotic at approximately the 11th male, with 2.83 ± 0.55 types per male) and the subsyllable part showed 22 types (becoming asymptotic at approximately the 12th male, with 8.92 ± 2.36 types per male). The syllable part showed 73 types and continued to produce new syllable types with 33.4 ± 5.07 types per male.
Figure 1. The map of recording sites of Daurian Redstart songs in South Korea.

Figure 2. Spectrogram showing the song structure of whistle, subsyllable, and syllable parts and syllable names from syllable catalogues (Figure S1) of the Daurian Redstart in South Korea.
**Figure 3.** Cumulative plot showing the number of syllable types produced by 20 Daurian Redstart males against the nth song sampled. Most of the songs reached the peak syllable types at approximately the 18th song. A1 to E4 is the ID of each individual.

**Table.** Summary of Daurian Redstart song information and the number of songs reaching maximum repertoire size. Bird ID A–E corresponds to the location of recording sites from Figure 1.

| Bird ID | # of song syllables detected | nth song when repertoire size reaches maximum | # of song syllables detected by 18th song | % of song syllable types detected by 18th song |
|---------|------------------------------|-----------------------------------------------|-------------------------------------------|-----------------------------------------------|
| A1      | 45                           | 19                                            | 42                                        | 93.3                                          |
| A2      | 39                           | 18                                            | 39                                        | 100.0                                         |
| A3      | 28                           | 17                                            | 28                                        | 100.0                                         |
| A4      | 40                           | 18                                            | 40                                        | 100.0                                         |
| B1      | 40                           | 18                                            | 40                                        | 100.0                                         |
| B2      | 44                           | 18                                            | 44                                        | 100.0                                         |
| B3      | 38                           | 15                                            | 38                                        | 100.0                                         |
| B4      | 28                           | 15                                            | 28                                        | 100.0                                         |
| C1      | 48                           | 17                                            | 48                                        | 100.0                                         |
| C2      | 40                           | 17                                            | 40                                        | 100.0                                         |
| C3      | 50                           | 18                                            | 50                                        | 100.0                                         |
| C4      | 44                           | 19                                            | 42                                        | 95.5                                          |
| D1      | 35                           | 19                                            | 33                                        | 94.3                                          |
| D2      | 37                           | 19                                            | 36                                        | 97.3                                          |
| D3      | 37                           | 20                                            | 35                                        | 94.6                                          |
| D4      | 37                           | 20                                            | 35                                        | 94.6                                          |
| E1      | 37                           | 19                                            | 35                                        | 94.6                                          |
| E2      | 47                           | 19                                            | 44                                        | 93.6                                          |
| E3      | 37                           | 20                                            | 36                                        | 97.3                                          |
| E4      | 46                           | 19                                            | 45                                        | 97.8                                          |
| Mean    | 39.9                         | 18.2                                          | 38.9                                      | 97.6                                          |
This study has examined the song structure and syllable repertoire size of Daurian Redstarts in South Korea. The song has the following defining characteristics: 1) the size of the syllable repertoire was determined by the 20th song per male at approximately 40 syllables per male (range: 28–50); 2) song syllables and their sequence in a series of songs varied within a male, while syllable types varied most in the syllable part of the song and least in the whistle part. Thus, the size of the song repertoire in particular was related to the syllable part of the Daurian Redstart song with a high degree of variability.

Similarities exist when comparing the song structure and syllable composition of the Daurian Redstart to another Redstart species, the Black Redstart (*P. ochrurus*; Cucco and Malacarne, 1999; Apfelbeck et al., 2012; Draganoiu et al., 2014). First, the syllable structure...
forming the first part of the Daurian Redstart song and the beginning strophes (a group of syllables repeated) of the Black Redstart song both start with whistle types. Second, both distinct strophes (the beginning and the ending strophes) of the Black Redstart song can be subdivided into 3 parts corresponding to the song structure of the Daurian Redstart (whistle, subsyllable, and syllable parts), even if the latter song consists of syllables more complex in number and type. To estimate repertoire size, the Daurian Redstart song tends to calculate the number of song syllables in the whole song, while the Black Redstart song measures the number of different combinations of each strophe, as the strophe most commonly contains the repetition of 1 syllable. Thus, the repertoire size of Black Redstart songs was much smaller (2.44 ± 0.2, mean ± SE, Draganoiu et al., 2014) than that of Daurian Redstart songs (39.9 ± 5.8, mean ± SD).

The song of the Daurian Redstart had highly variable syllable composition in consecutive songs; some songs were very dissimilar from each other, while others were more similar, merely adding new syllables or shortening the syllables in their song composition. Even though the songs have distinguishable similarity with three structural song parts, overall songs lacked an obvious song type. Counting syllable types is appropriate for estimating the song repertoire size in this species. A similar analysis has been applied in several other species. Due to the very flexible song structure of Great Reed Warblers, the estimated size of the song repertoire was equal to the total number of song elements (Catchpole, 1983, 1986). The Willow Warbler’s and the Sedge Warbler’s songs were also similar to that of our species: their songs showed temporal patterns in the song part (whistle part) and variable part (syllable part) and contained 3 sections (start, middle, and end) with various syllable types at each section, and their syllables in song showed high transitions in sequence and varied in structural detail (Catchpole, 1976; Gil and Slater, 2000). Thus, these species were characterized by a high variation of song composition with shared syllables and it would be difficult to categorize them homogeneously within specific song types.

Our results on the syllable-level repertoire size could provide a reliable way to measure the song repertoire of the Daurian Redstart. After sampling the 18th song per male, few syllable types were added to the songs, indicating that the syllable type size of Daurian Redstarts peaks before the 20th song. The highest number of syllable types may be regarded as the individual’s song repertoire size. Moreover, the addition of new syllables was gradually reduced with increasing numbers of males, meaning particular syllables might be used very often, as in the song of the Willow Warbler (Gil and Slater, 2000). It can be inferred that there are core syllables in the songs (Figure 4). However, syllable addition in the whistle and subsyllable parts was relatively limited with a lower degree of variability, and the syllable repertoire size can be considered to be related to the syllable part of the song. It is suggested that the cue of individual identity might exist in the syllable part of the song, contrary to the suggestion of Huang et al. (2012), while the cue of song dialect exists in the whistle and subsyllable parts (Podos and Warren, 2007; Průchová et al., 2017). Thus, further research on song variation of the Daurian Redstart should focus on the syllable variation at the interindividual level and the whistle and subsyllable variation at the interpopulation level.

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Figure S1. Syllable types in whistle, subsyllable, and syllable parts of 400 songs of 20 individuals from five population samples in 2015 and 2016 in South Korea.
Figure S1. (Continued).