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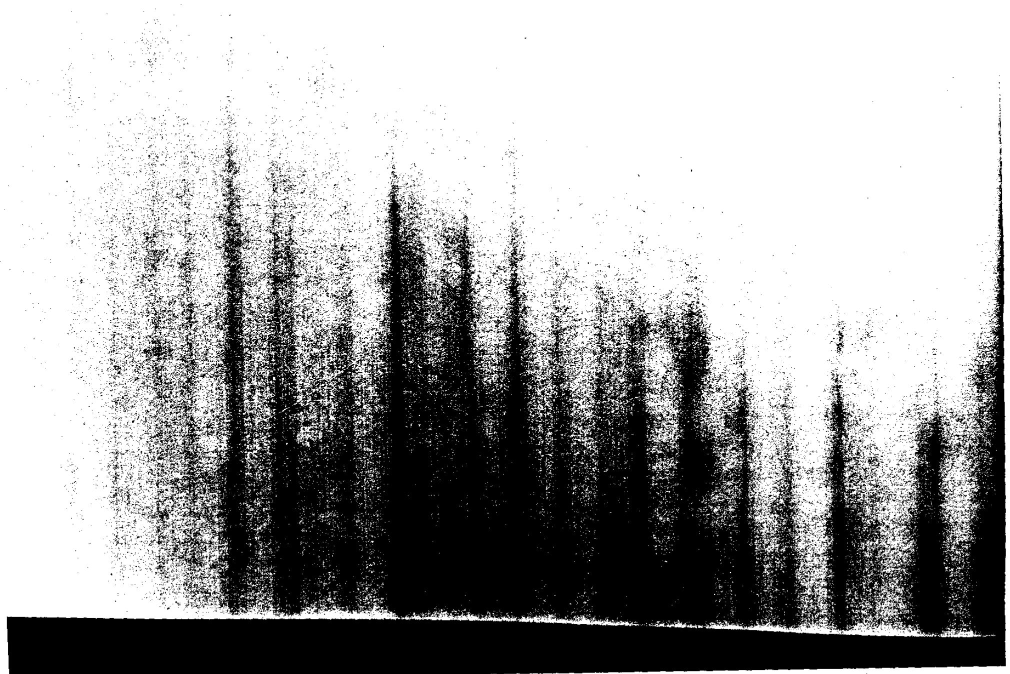

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ABSTRACT

Bird song researchers have not agreed on a common set of units of analysis by which birds' songs of various different species might be described. Analysis of 50 papers reveals 28 unit designations and considerable variation in their application despite only three different methods for identifying units. The lack of consensus on units arises from the fact that units generated by the same methods at different levels of organization are given different names. A method for designating bird song units is offered for discussion which uses the concept of level of organization to stress the fundamental unanimity of method. It is hoped that consideration of this method will lead ultimately to greater standardization in the protocols by which researchers generate and name bird song units.

INTRODUCTION

Bird song is among the most thoroughly studied complex behaviors. Yet the function of variations in its form is not well understood. The absence of the broad-based comparative analysis necessary to produce such an understanding may be due in part to the fact that bird song researchers have not agreed on a common set of units of analysis by which birds' songs of various different species may be described.

Given the need for such a system, it is remarkable that none has been developed. Shiovitz (1975) attempted to standardize terms for describing bird song components. He proposed nine terms to apply to units depending on their duration and the methods used by investigators to identify them. Of these, Shiovitz found that four kinds had been referred to as "phrases" by various authors, five kinds as 'notes', three as 'syllables' and four as 'elements'. Despite this overlap in the use of terms, Shiovitz also found that 20 different terms had been used to describe the 8 types of units he identified. Since Shiovitz's paper the situation has become more chaotic. In a preliminary survey of the literature in preparation for this research, we found at least 9 terms that have been introduced since Shiovitz's paper to refer to units of approximately the same duration and composition as those cited by Shiovitz.

Consequently, we set about to do an analysis of the units in use by bird song investigators. This project might result in either of two terminological outcomes beneficial to the development of our understanding of bird song:

[1] We might discover a broad consensus in how terms are used. We might therefore be able to attach some of the commonly used terms to particular hierarchical levels in the systems or to units of particular mode of generation or duration. This outcome would be standardization of some of the commonly used labels for song units.

Or [2] we might discover that there is little consensus in the use of terms but a broad consensus in the methods used to identify terms. Such an outcome would suggest that clarity and simplicity of communication among bird song specialists would be increased by adopting a system of song unit nomenclature based on this unanimity of method.

METHODS

We searched journals, reprints and the libraries of colleges for journal articles in which song systems were described. At one time or other, we handled more than 100 papers, but we make no claim that this sample was exhaustive, random or representative either of birds or of authors, because it was biased strongly by the availability of materials.

From this original group of papers, many were eliminated because we could not decipher how the authors recognized the units they discussed. From the group of papers that we could understand, a smaller number was selected to provide the song descriptions that we analyzed. Even among the papers we ultimately used, a surprising amount of detective work was required to discover what the authors meant by a particular term. In general we selected only one paper to serve as our authority on each species. Where two authors wrote on the same species, we chose as our authority the more complete, the more explicit, and the more recent paper, roughly in that order of priority. In a few instances, where two papers made a complementary contribution to our understanding of a particular species, we used one paper as our basic reference and supplemented its description with information from the other.

RESULTS

The results reveal a high level of consensus among bird song investigators concerning how to generate a system of bird song units but great diversity in how those units should be named.

A. Methods of Generating Units

In dividing the song stream into chunks for analysis, authors have used only three methods.

1. The Temporal Method (T). The temporal method takes account of the pauses in the song stream. The researcher visually scans or measures the spectrographic record and assesses the relative frequency of pauses of different durations. Such an assessment usually reveals one or more modes in the frequency distribution of pauses: that is, pauses of some durations are much more frequent than others. The traditional way to differentiate temporal units of different orders of duration is to set boundaries between the modes in the pause distribution at points where few pauses are actually observed.

2. Morphological Methods (M). The other two methods for making song units are based on morphological characteristics of sounds. In a morphological method, the sound stream is broken into segments by taking account of repeated patterns of sound. Morphological analysis is most often used to generate higher order units in a sound stream that has already been divided into basic temporal units. The investigator makes a sound spectrograph of each temporal unit and then sorts the spectrograms into piles on the basis of their similarities and differences. By this method, each pile comes to represent a morphological type (or 'morph') and the members of the pile the instances of the morph. For a great many songs, this procedure leads unambiguously to the creation of basic unit morphs. Even though the members of the different piles may differ in small details, members of the same pile vary so little that independent sorters are usually able to duplicate one another's work exactly (e.g. Boughey and Thompson 1976).

Once basic temporal units have been classified morphologically, morphological considerations can be used to divide the sound stream into units of higher order. Only two methods are commonly used to create higher order morphological units.

a. Morphological Sequence Analysis (Ms): Examination of the song stream will in some species reveal portions of the stream that are repetitions of other portions. A higher order 'chunk' of the song stream can thus be defined as a precisely repeated sequence of basic unit morphs. These sequences can be identified unambiguously as units because each morph within the sequence never occurs in the absence of the others and because the sequence is not regularly preceded or followed by any other morphological types. The sequence is thus itself a unit of recombination.

b. Morphological Runs Analysis (Mr): In a runs analysis, the song record is divided into units by identifying homogeneous sequences of morphological types. If a song consists of homogeneous sequences of one morphological type, followed by homogeneous sequences of another type, followed by homogeneous sequences of a third type, etc., then higher-order units can be identified by dividing the song stream at shifts from one song unit type to another. This technique is used to identify 'bouts' in song sparrows *Melospiza melodia* (e.g. Mulligan 1966) and 'phrases' in mockingbirds *Mimus polyglottos* (e.g. Howard 1974). Furthermore, if the song stream contains heterogeneous sequences in a record that consists mostly of homogeneous sequences, then the stream can be divided at the boundaries of the heterogeneous and homogeneous sequences. Such a technique is also used on song sparrows whose song is traditionally divided into 'trills' (homogeneous sequences) and 'note complexes' (heterogeneous sequences) (Mulligan 1966).

B. Identification of Units

Having found a broad consensus on how to divide bird songs into units, we examined the data for evidence of a consensus concerning how to name them. But in the course of our review of the 50 song descriptions, we encountered at least 28 unit identifications (Table 1). More than half of these terms occurred only once. The seven most frequent terms—song, syllable, note, bout, phrase, trill and element—were used in a variety of different ways. For instance, the durations and intervals of units with the same name often ranged over two or more temporal orders of magnitude and often applied to units of different hierarchical level (Table 2). Perhaps most unsettling of all was the lack of relationship between the name given a unit and method by which it was generated. Most terms designated units that had been generated by at least two of the three methods (Table 3).

TABLE 1

Unit designations encountered in the descriptions of fifty species in the bird song literature.

Designation	Frequency of use	Designation	Frequency of use
song	42	compound-note	1
syllable	25	pattern	1
note	23	part	1
bout	16	flappet	1
phrase	16	multiple-song-unit	1
trill	9	period	1
element	6	tour	1
burst	4	series	1
figure	4	sub-syllable	1
performance	3	strophe	1
sequence	3	string	1
caw	3	sound-complex	1
combinations	2	song-patterns	1
syllable patterns	2	song-motif	1

TABLE 2

The order of magnitude of the durations/intervals, in log seconds, of units designated note, element, syllable, phrase, trill, song, or bout. Values in the table are the number of instances found where the unit was ascribed that duration (above diagonals) or interval (below diagonal) duration/interval, log seconds.

	−2	−1	0	+1	+2
note	5 / 9	18 / 3	0 / 1		
element	0 / 3	5 / 3	1 / 0		
syllable	5 / 17	20 / 8			
phrase	0 / 3	11 / 10	5 / 2		
trill	0 / 3	6 / 5	3 / 0		
song		1 / 2	37 / 11	1 / 5	1 / 0
bout				3 / 2	8 / 0

TABLE 3

Method used to generate each of the commonly used units: T = temporal method, Ms = morphological method (sequence), Mr = morphological method (runs analysis).

	T	Ms	Mr
note	23	0	0
element	5	0	1
syllable	11	12	2
phrase	3	5	8
trill	0	1	8
song	35	3	4
bout	8	0	8

DISCUSSION

Given the consensus on methods, why have bird song experts been so inconsistent in assigning names to them? The answer seems to relate to levels of analysis. When the same method has been used to create units of different magnitude, observers have used different names for the units thus created. Thus the entire range of units has been generated through the use of a relatively few organizing principles at many different levels of analysis. What this analysis suggests is that the concept of levels of analysis could be used to build a system to designate any song unit with just a few terms, instead of the dozens now in use.

From these considerations arose the concept of a song formula to represent the structure units of a bird's song. Earlier attempts (e.g. Bondesen 1979) at producing a song formula applicable to many different species' songs have relied upon terminology which is not widely accepted and have only allowed analysis at a limited number of levels. We would like to propose a song formula which employs neutral terminology and which allows analysis at an indefinite number of levels. Analogous formulae have been used in other fields of biology to condense a large amount of comparable information into a single line of text, for example, the floral formula in botany and dental formulae in comparative anatomy (Parker 1987). The formula offered here describes a song as a sequence of progressively more inclusive units. The basic format for the song formula is as follows:

$$1(T, Ms, \text{ or } Mr) + 2(T, Ms, \text{ or } Mr) + \ldots + N(T, Ms, \text{ or } Mr)$$

where the numbers indicate the hierarchical level of the unit from low to high and the letters indicate the method by which the unit was determined.

How a song formula is assigned to a song is best understood if it is illustrated by a familiar example. According to Mulligan (1966) the song of the song sparrow has at least five hierarchical levels (Figure 1). Lowest of these is the 'note'. A note is defined as a 'sound' represented by a 'continuous trace' on the sound spectrograph. Notes are thus 1T units (ie, first order temporal units) in this system. They were identified as units by the fact that they were sustained emissions of sound separated from one another by pauses and as first-order units because there was no mode in the frequency distribution of all pauses that had a lower value than the mode of pauses between notes.

At the next level is the syllable, a sequence of one or more notes that is recognizable as a unit because it is precisely repeated. (In this nomenclature, a note can also be a syllable if it is a minimal unit of recombination). Syllables are thus 2Ms units. The subscript 's' is used to remind us that sequencing was the morphological principle used to

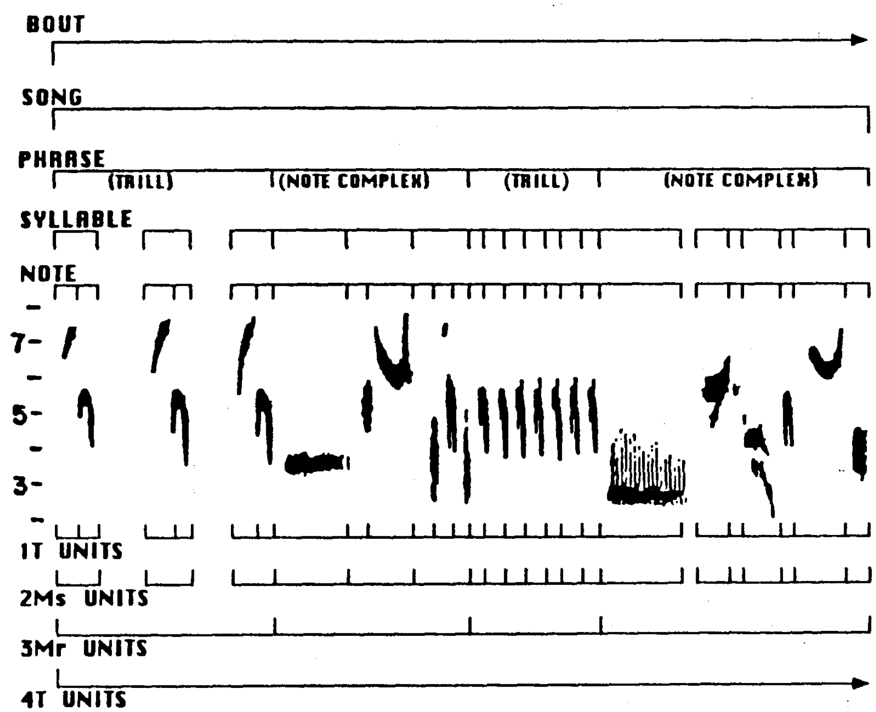

Figure 1. A song sparrow song. Notes are 1T units, syllables are 2Ms units, phrases are 3Mr Units, and songs are 4T units. Fifth order units, bouts, are groupings of songs. 2.4 seconds are shown. (Adapted from Kroodsma 1977, p. 391, and Mulligan 1966).

generate the units. Syllables and notes are themselves organized into third order units known as phrases. In one kind of phrase, the trill, the syllables are organized into runs of similar syllables. Bounded by these trills and by the beginnings and ending of the songs are heterogeneous sequences called 'note complexes.' Trills and note complexes together comprise the two morphological types of phrases. Since both types of phrases are groupings of second order units and since they are generated from the analysis of runs of morphs, they are here designated as 3Mr units. Here the subscript 'r' signifies that runs analysis was the morphological principle used to generate the unit.

Phrases are in turn clustered together into performances called 'songs'. Songs are identified by the pauses between them, which are of the order of several seconds. Songs are thus temporally based clusterings of third level units and are designated here as 4T units. Each song may be morphologically classified into types based on its phrase structure. Song sparrows characteristically sing a homogeneous sequence of one song morph before changing and singing a homogeneous sequence of another, thus passing eventually through their repertoire of song types. Such homogeneous sequences are known as bouts, and are designated as 5Mr units in the present system. Thus, the song sparrow would have five levels in its system and its song formula would be: 1t (=notes) + 2Ms (= syllables) + 3Mr (= phrases: trills or note complexes) + 4T (= songs) + 5Mr (= bouts), or simply

$$1T + 2Ms + 3Mr + 4T + 5Mr.$$

Figures 2 and 3 show similar song unit and formula comparisons for the northern mockingbird and the crow *Corvus brachyrhynchos*.

To give each formula a temporal scale it may be useful to include duration information in the formula. This is accomplished by following each term in the formula with its duration and interval, represented as powers of 10 sec (for the purposes of this discussion, we have estimated

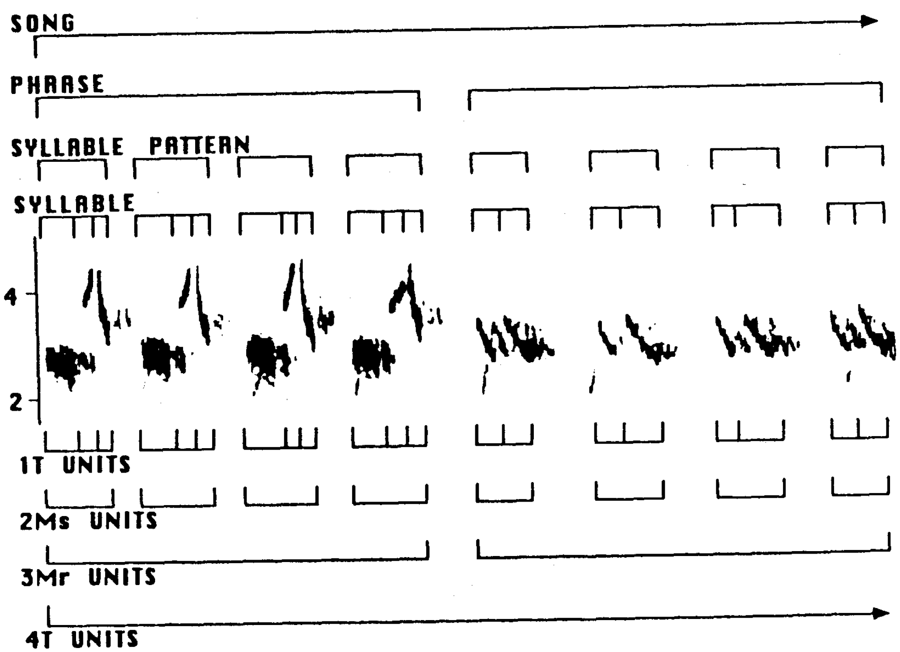

Figure 2. Part of a northern mockingbird song. Syllables are 1T units, syllable patterns are 2Ms units, phrases are 3Mr units, and songs are 4T units. 2.2 seconds are shown. Spectrogram made on a Quadra 700 running Canary 1.1 software (sampling rate 22 kHz, filter bandwidth 350 Hz, Hamming window function).

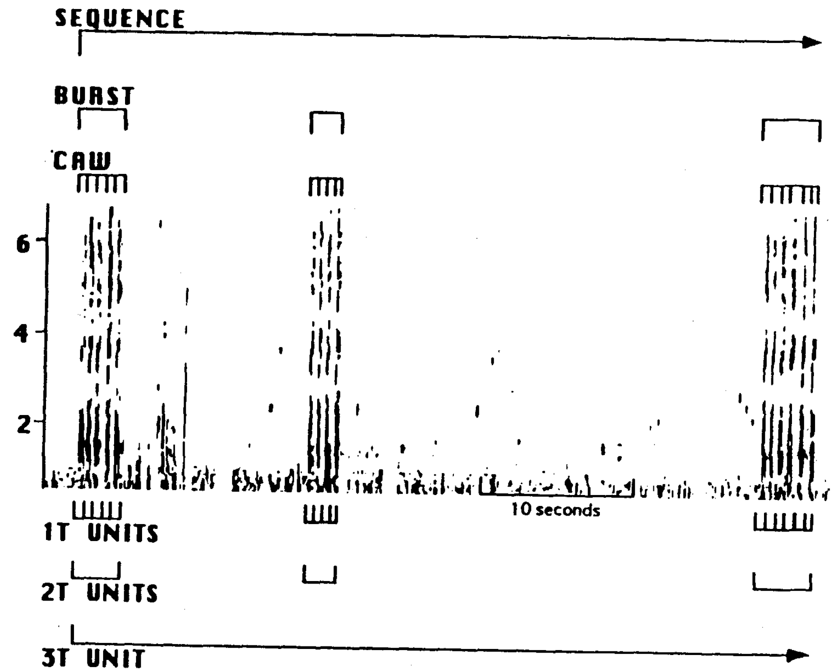

Figure 3. Ordinary cawing of the common American crow. Caws are 1T units, bursts are 2T units, and sequences are 3T units. Approximately 50 seconds are shown. Spectrogram made on a Quadra 700 running Canary 1.1 software (sampling rate 22 kHz, filter bandwidth 350 Hz, Hamming window function).

from our own knowledge the magnitude and duration of higher order units in song sparrow song, c.f. Mulligan 1966). In this form, the song sparrow's song formula becomes

$$1T[-1,-1] + 2Ms[-1,-1] + 3Mr[-1,-1] + 4T[0,N] + 5Mr[N,N]$$

where 'N' indicates that no information was available to assess the magnitude of the unit.

The song formula puts into a single line a large amount of information concerning the song. Its potential usefulness can be evaluated by comparing familiar species in Table 4, in which 12 species are listed in order of number of levels in their song systems as described by the scientists who studied them. Many of the species are found where one would expect them: the paridae are in the upper half of the list, the mockingbird, brown thrasher and canary *Serinus canarius* in the lower half. But there are some surprises: the red-winged blackbirds *Agelaius*

TABLE 4

Song formula for 12 birds tabulated with the Linnean name, common name, and the authority from whose work the formula was derived.*

Genus	Species	Common name	First author	Formula
Vireo	*olivaceus*	Red-eyed vireo	Lemon	1T(-1,-2) + 2T(-1,-1).
Carpodacus	*mexicanus*	House finch	Mundinger	1T(-1,-2) + 2Mr(0,N).
Sturnella	*neglecta*	Western meadowlark	Falls	1T(0,0) + 2Mr(2,0).
Dumetella	*carolinensis*	Catbird	Thompson, W L	1T(-1,-2) 2T(-1,-1) + 3T(2,N).
Parus	*atricapillus*	Black-capped chickadee	Ward	1T(-1,-1) + 2T(0,N) + 3T(N,N).
Corvus	*brachyrhynchos*	American crow	Thompson, N	1T(-1,-1) + 2T(0,1) + 3T(1,2).
Mimus	*polyglottos*	Mockingbird	Howard	1T(-2,-2) + 2Ms(-1,-1) + 3Mr(0,-1) + 4T(0,N).
Serinus	*canarius*	Canary	Nottebohm	1T(-1,-2) + 2Ms(-1,-2) + 3Mr(0,-1) + 4T(0,N).
Toxostoma	*rufum*	Brown thrasher	Boughey	1T(-2,-2) + 2T(-1,-2) + 3T(-1,-1) + 4T(2,N).
Agelaius	*phoeniceus*	Red-winged blackbird	Smith, D G	1T(-1,-2) + 2Ms(-1,2) + 3Mr(-1,-2) + 4T(0,N) + 5Mr(2,N).
Melospiza	*melodia*	Song sparrow	Mulligan	1T(-1,-1) + 2Ms(-1,-1) + 3Mr(-1,-1) + 4T(0,N) + 5Mr(N,N).
Telmatodytes	*palustris*	Long-billed marsh wren	Verner	1T(-2,-2) + 2Mr(-2,-2) + 3Mr(-1,-1) + Ms(0,N) + 5(N,N) + 6T(N,N).

*NOTE: Durations and intervals are in many cases estimated from typical sound spectrograms offered by authors. "N" indicates that insufficient information was available to assign a value to the duration or interval of the unit in question.

phoeniceus, which would seem to sing a relatively simple song, are nonetheless listed along with the song sparrow and the long-billed marsh wren *Telmatodytes palustris* as having a five level system, whereas the housefinch *Carpodacus mexicanus* and the catbird *Dumetella carolinensis*, which would seem to sing relatively complex songs, are listed as having two and three level systems, respectively.

These anomalies largely reflect differences in the research protocols of the investigators. A formula can be long and short not only because the bird sings a simple or a complex song but because the scientist describing that song decided to describe the song grossly or in fine detail. One scientist might make a decision to further analyze the elements of a song into finer elements and so the number of levels in the song formula is increased. Another might increase the number of levels by analyzing the higher order groupings of the song. Thus the number of levels in a bird's song formula is as much a product of the ambitions and interests of the researcher as it is of the complexity of the song itself.

CONCLUSION

Until now, bird song researchers have widely shared the attitude that a standard nomenclature is neither possible nor beneficial. The despair about the possibility of such a system seems often to be based on an uneasiness concerning the relation between human hearing and the hearing of the birds (Kroodsma 1982). This uneasiness is well founded but not relevant. We agree that there is no guarantee that the dimensions used by humans to classify sounds are the dimensions of importance to the birds. But as long as the functional organization of songs is not well understood, scientists (e.g. Hamilton and Zuk 1982, Read and Weary 1990) will continue to describe songs in human terms. That being the case, it behoves us to standardize and formalize our use of the human-based units until better ones are available.

Not only is the adoption of this system possible, but we think it will have important benefits. At the very minimum, it will be useful for describing the behavior of scientists. Remember that despite the dozens of bird song terms in use, only three methods of generating bird song units have ever been used. The present bird song nomenclature makes systems of song units seem much more idiosyncratic than they actually are. The system proposed here should permit researchers to communicate with one another concerning how they have applied these common methods to their respective species.

Beyond the beneficial effects on how investigators communicate, it may also have important effects on how they observe and describe their subjects. Using a song formula should encourage researchers to collect a basic common body of information about each song they study. Just adopting simple conventions for the upward and downward bounds of a song unit system would largely alleviate the problem of incommensurability of song descriptions encountered above.

While it is obvious that no system will accommodate every bird vocalization, we think adoption of the some system of bird song description will help to achieve greater standardization of unit designations in the literature and a more standard protocol for gathering and providing information about song. We hope that discussion of the system offered here will ultimately serve these ends.

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