A METHOD FOR THE OBJECTIVE STUDY OF BIRD SONG AND ITS APPLICATION TO THE ANALYSIS OF BEWICK WREN SONGS

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The structures of the songs of birds are usually so complex and variable that the human ear is unable to perceive them accurately. For this reason nearly all studies of bird song have been largely of a subjective nature and have furnished little information for the development of a precise knowledge of bird song itself or for the support of taxonomic and behaviorial investigations.

For the objective analysis of bird song suitable methods are required for the measurement of frequency, amplitude, and time. For a number of years methods have been available for the quantitative determination of each of these factors, but little attention has been given to the analysis of the complex patterns of tones found in the songs of birds. Brand (Auk, 52, 1935:40-52) made measurements of the pitch and time of bird songs by using a low-power microscope in examining recordings made on sound tracks on motion picture film. In that paper and in a later one (Brand, Auk, 55, 1938: 263-268) he reported the lengths of the notes and songs of a number of birds. He also listed for a large number of passerine species the maximum, minimum and mean values of the "pitch-giving" frequencies found in their songs, and for the Meadowlark, Goldfinch and Bob-white Quail he presented graphical representations of examples of their songs or calls plotted on charts of pitch versus time. Axtell (Auk, 55, 1938:481-491) employed Brand's method in his studies of the song of the Kirtland Warbler. The "sound spectrograph," which was developed by Potter and co-workers in 1945 for the analysis of sounds of speech, prepares from a recorded sound of short duration a chart depicting along a time scale all the major frequencies present in the sound. Several examples of records prepared on this instrument from bird song recordings supplied by the Albert R. Brand Bird Song Foundation appear in the publication "Visible Speech" (Potter, Kopp and Green, 1947, D. Van Nostrand). Commercial versions of the "sound spectrograph" have recently been placed on the market.

The purpose of this paper is to describe a new method for the analysis of bird song. The method has limited possibilities for use in the field, but for many reasons it is of great potential usefulness when applied to the analysis of recorded songs. An assembly of commercially available instruments has been devised which produces inked tracings representing frequency with respect to time. These tracings may be used to study the patterns of notes, the pitch and duration of each note, and the intervals between notes and between successive songs. The equipment to be described does not measure amplitude, but this measurement can be made by the addition of relatively simple circuits and suitable calibration of the recording equipment. Those factors which contribute to the timbre of bird songs cannot be measured except by resorting to considerably more complex equipment and techniques.

EQUIPMENT

Figure 1 is a block diagram of the instruments used in this work. The nature and function of each instrument will be described in the following paragraphs. Although the instruments are designated by the names and model numbers of specific manufacturers, it is not implied that equivalent instruments of other manufacturers are not equally suitable.

Tape recorder.—The Magnecord tape recorder (Model PT6–JAH) is used also in the field for the recording of bird songs. In the field the synchronous motor of the recorder is operated from a 110-volt, 60-cycle power supply accurately controlled with respect to frequency. This is important, for in order to permit the greatest accuracy in the measurement of pitch and time, the tape must be driven at the same speed during recording as during reproduction for analysis. The Magnecord recorder is provided with a 600-ohm output, which is connected to the mixing circuit, and with a 16-ohm output, which is connected to the Brush AC amplifier.

Audio oscillator.—The Hewlett-Packard audio oscillator (Model 201B) has a frequency range of 20–20,000 cycles per second (cps), which includes all frequencies likely to be encountered in bird

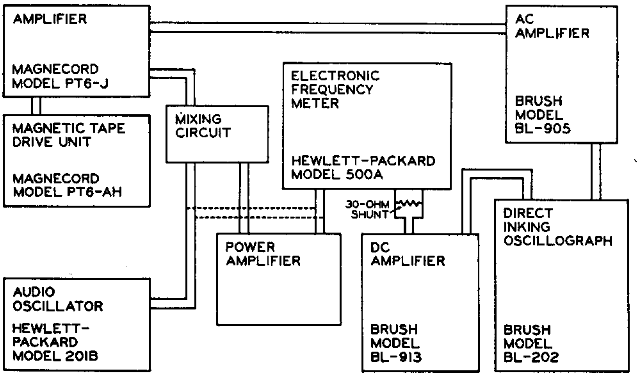

Fig. 1. Block diagram of instruments used for the preparation of oscillograph tracings showing the pitch and time factors of recorded bird songs.

songs. During the reproduction of recorded bird songs into the frequency meter, the 600–ohm output of the oscillator is connected to the mixing circuit. In this function a signal of low frequency is generated by the oscillator and mixed in the mixing circuit with the reproduced bird songs. Tape noise is of a random character and causes the frequency meter and oscillograph to respond in a haphazard manner in the silent periods between bird song notes. By mixing the low frequency signal with the bird songs, in the silent periods the oscillograph pen is drawn to the baseline of the oscillograph chart. The frequency of this signal is therefore chosen to correspond to that represented by the baseline, and its amplitude must be in the range between the amplitude of the noise inherent in the tape and that of the notes of lowest amplitude in the bird songs.

The oscillator signal may also be used to override background sounds inadvertently recorded with the bird songs. Their influence can be eliminated entirely without interference with the bird song notes of lowest amplitude, if the amplitude of these sounds is below the amplitude range of the bird songs. Useful tracings may be made by this method when the amplitude ranges overlap, but detailed analyses are not possible.

The oscillator is also used to prepare tapes containing signals of known frequency for calibration purposes. In addition, the oscillator provides a means of adjusting the range of the oscillograph. For this function the oscillator is connected directly to the frequency meter as shown by the dashed lines in figure 1.

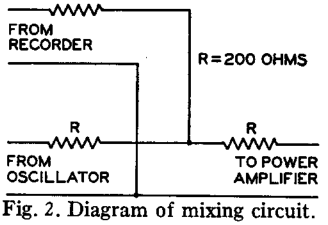

Fig. 2. Diagram of mixing circuit.

Mixing circuit.—The mixing circuit (fig. 2) is a simple resistive network. It permits the mixing of a signal of low frequency from the oscillator with the recorded bird songs reproduced by the recorder. The inputs have impedances of 600 ohms and the 600–ohm output is connected to the power amplifier.

Power amplifier.—The power amplifier provides sufficient amplification to produce at least 20 volts across the high-impedance input to the frequency meter when the maximum voltage across the 600–ohm output of the recorder amplifier is 0.75 volts. These specifications are given to ensure that the bird song notes of lowest amplitude will be fed to the frequency meter at a level of at least 0.2 volt. The ratio of the maximum to the minimum voltages at the input to the frequency meter (100/1) represents an amplitude range of 40 decibels (db), which is believed to be somewhat greater than is encountered in most bird songs. However, the margin is considered to be desirable. For proper matching to the mixing circuit the input of the power amplifier should have an impedance of 600 ohms. If the power amplifier has a high impedance input, the output of the mixing circuit should be loaded with a 600–ohm resistor.

Frequency meter.—The Hewlett-Packard Electronic Frequency Meter (Model 500A) is an instrument the direct current output of which, in milliampères, is proportional to the frequency of the input signal. This proportional relationship holds with an accuracy of about two per cent as long as the voltage of the input signal is between 0.2 and 200 volts. The output circuit is designed to operate into a milliammeter of 1400–ohm impedance. Under the conditions used in this work the load across the output is 30 ohms, but the deviation from normal operation exhibited by the instrument is accounted for by the method of frequency calibration.

The Hewlett-Packard Electronic Frequency Meter responds to the frequency of greatest amplitude. This response to a single frequency occurs without interference as long as the harmonic frequencies have 3 to 5 db less amplitude. When the difference in amplitude of two or more frequencies is less than 3 to 5 db, the meter cannot distinguish the predominant one and oscillates between them. In order to determine the pitch of notes of this nature, filters are employed to reduce the amplitude of the interfering frequency or frequencies.

DC amplifier and oscillograph.—The Brush DC Amplifier (Model BL–913) and Brush Direct Inking Oscillograph (Model BL–202) ordinarily are used for the continuous recording of direct current voltages. The Model BL–202 oscillograph is a two-channel instrument with two magnetically driven pens which write side by side on a double-channel paper chart. The DC amplifier drives one of the pen motors; the second is driven by the AC amplifier as described below.

By placing a 30–ohm shunt across the line between the frequency meter and the DC amplifier, the amplifier and oscillograph perform as a recording direct current milliammeter which will respond to changes in the current of the output of the frequency meter as long as the changes do not occur at a rate greater than about 100 times per second.

AC amplifier and oscillograph.—The Brush AC Amplifier (Model BL–905) and the second channel of the oscillograph are connected to the 16–ohm output of the tape recorder for the purpose of making a time calibration record simultaneously with the making of the frequency record on the first channel.

METHOD

In the songs of birds changes in frequency may occur at a rate greater than 100 times per second, which is the approximate upper limit of the response of the magnetic motor of the oscillograph. For this reason it has been found that it is necessary, for the preparation of oscillograph tracings, to reproduce the bird songs at tape speeds less than that at which they were recorded. Tracings prepared from recordings reproduced at half-speed are useful for the study of the patterns of notes in songs and for the measurement of the duration of songs and notes, the intervals between notes, and the intervals between successive songs. However, tracings prepared in this manner may not show all the frequency changes involved. Consequently, for the detailed analysis of pitch the recordings are reproduced at one-eighth the speed at which they were recorded. When recordings are reproduced at reduced speeds the pitch of all tones is lowered by one octave for each 2 to 1 reduction, and the time factors are doubled.

During the preparation of tracings with the equipment described, the chart, on which a grid is printed, is driven through the oscillograph at a controlled, constant speed. If there is no signal fed into the system from the tape recorder, the oscillograph pen (channel 1) rides on the baseline of the chart due to the signal from the audio oscillator, which is adjusted to perform this function. When relatively pure tones of sound are reproduced by the tape recorder, the oscillograph pen traces a line that is farther from the baseline the higher the pitch of the tone.

In order to calibrate the system with respect to frequency, a calibration tape is prepared by splicing together a series of short strips of tape on each of which is recorded a tone of known frequency. The calibration tape is spliced to the tape on which the bird songs are recorded and is subjected throughout the analytical procedures to the same operations as the tape containing the bird songs. Thus, at whatever tape speed used in the reproduction of the bird songs, a calibration curve is traced by the oscillograph immediately before (or after) the bird songs are traced, and the deflections of the oscillograph pen due to the tones of the bird songs are interpreted in terms of fre-

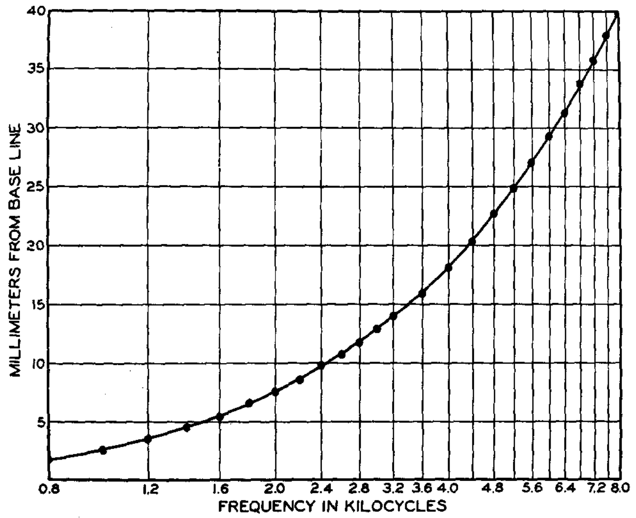

Fig. 3. Calibration curve for the interpretation of oscillograph deflection in terms of frequency.

quency by comparing them with the deflections due to the tones of known frequency on the calibration tape. Figure 3 is a plot of data obtained from an oscillograph tracing of a calibration tape reproduced at one-eighth speed. The dots on this frequency calibration curve indicate the frequencies used on the calibration tape, which covered the range from 800 to 8000 cps, and relate these frequencies (horizontal logarithmic scale) to the extent of deflection of the oscillograph pen from the baseline (vertical linear scale).

Time factors in the recorded bird songs are established by means of the following procedure. A 100–cps signal is recorded on tape, using the same recorder and tape drive speed used in the recording of the bird songs. A strip of this tape is also spliced to the tape on which the bird songs are recorded. During the preparation of half-speed tracings the AC amplifier and the pen of the second channel of the oscillograph respond to the 100–cps signal (50 cps when reproduced at half-speed) and there is recorded on the oscillograph chart a sine wave each cycle of which covers a length of chart equivalent to an elapsed time of 0.01 second. A portion of an oscillograph chart showing a time calibration tracing is reproduced in figure 4. It is seen that by appropriate measurements and calculations the duration of time represented by the transverse reference lines of the chart is readily ascertained.

ANALYSIS OF BEWICK WREN SONGS

The use of the analytical method is illustrated by its application to the analysis of a series of 22 recorded songs of the Bewick Wren (*Thryomanes bewickii*). This series

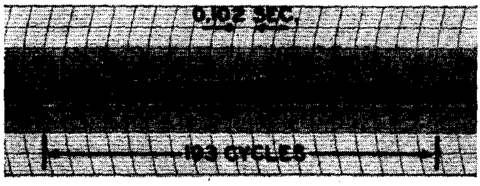

Fig. 4. Portion of oscillograph chart showing a time calibration tracing. The oscillatory line is made by a 100-cps signal reproduced by the tape recorder. The figures indicate the measurements and calculations required to determine the duration of time represented by the vertical (curved) reference lines.

of songs was recorded on May 23, 1951, about five miles west of Walker Pass in the eastern extreme of South Fork Valley, Kern County, California. The series was an unbroken sequence recorded from a male perched in a Joshua tree about 100 yards from the nest, from which young had left within the previous two or three days.

The recordings were made at a tape speed of 15 inches per second (ips) using plastic-base, red-oxide tape. The capacitor-type microphone (Stephens Manufacturing Corp., Model C–1C) was mounted in a parabolic reflector of 30-inch diameter located 45 feet from the wren.

Half-speed oscillograph tracings were made of the 22 songs by the method described in the previous sections of this paper. Examination of these tracings showed that all the songs were of the same pattern. In each of the songs the sequence of notes was the same, except for variations in the numbers of certain repetitive elements. In view of the similarity of the songs, one example was selected for a detailed frequency analysis, which is discussed below. The song selected for this purpose (no. 3 in the sequence of 22) is designated the representative example of the pattern. The pattern will be referred to as Bewick Wren pattern 1.

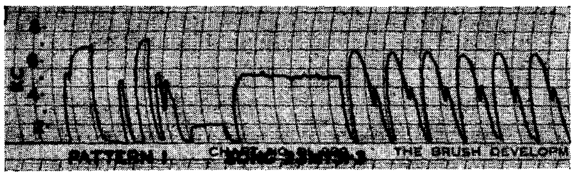

Fig. 5. Portion of oscillograph chart showing a half-speed tracing of the representative example of pattern 1 of the Bewick Wren song. The song number indicates the day, month and year of the recording and the number of the song in the sequence of 22 songs. The scale at left indicates frequency in kilocycles. The dots above the tracing are half-second timing marks.

The half-speed tracing of the representative example of Bewick Wren pattern 1 is reproduced in figure 5. A frequency scale is at the left and quarter-second timing marks appear above the tracing. Attention is drawn to the fact that the tracing is skewed to the left because the oscillograph pen swings in an arc. In addition, the frequency scale is greatly compressed relative to the time scale. In order to correct these deficiencies and to represent the song in a manner which will permit comparison with songs analyzed by other equipment or other methods, a detailed frequency-time analysis of the pattern 1 song was made and the results plotted on semi-logarithmic coordinates.

To accomplish the detailed frequency analysis of the example, the original recording of this song and the frequency calibration tape were re-recorded by reproducing them from a recorder operating at 7.5 ips into another operating at 60 ips. Eighth-speed oscillograph tracings were then prepared by reproducing the copies of the song and the frequency calibration tape at 15 ips. By the use of a frequency calibration curve similar to that reproduced in figure 3, the frequencies of the tones of the notes were determined at a suitable number of critical points on the eighth-speed oscillograph tracing. The elapsed time between the beginning of the first note and each of the critical points was determined by linear measurements on the oscillograph chart. The time represented by the total linear length of the tracing of the song was calculated from the half-speed tracing by making use of the time calibration tracing prepared simultaneously with it. The time represented by each critical point was then calculated by means of the following equation:

$$\text{Time from beginning of song to each critical point (sec.)} = \frac{\text{Linear distance from beginning of song to critical point (mm.)}}{\text{Linear distance from beginning to end of song (mm.)}} \times \text{Length of song as determined from half-speed tracing (sec.)}$$

The data obtained by the detailed frequency-time analysis of the example of pattern 1 were used to prepare figure 6. The vertical axis represents frequency in kilocycles per second (kc) on a logarithmic scale. The horizontal axis represents time in seconds on a linear scale. The pitch of the notes comprising this song varies from 2150 to 7300 cps. The gap between the beginning of the song (zero time) and the beginning of the first note as represented in figure 5 results from the fact that during the bird's attack on this note the structure of the sound was so complex that the pitch could not be resolved. Attention is called also to the structure of the trill which occurs in the middle of the song. Because it contains too many notes to depict it accurately on the scale at which figure 5 was drawn, it was necessary to show it in a symbolic fashion. However, the symbolism shows the nature of the structure of the trill—a series of very short notes on alternately higher and lower frequencies. In the figure the higher line of notes is at the highest pitch found in the trill and the lower line is at the lowest pitch.

The pattern 1 song can be divided into three parts. Part 1 is that portion occurring before the trill. It is difficult to describe except in general terms: a non-repetitive sequence of notes the pitch of which varies over a wide range of frequencies. The trill separates part 1 from part 3, which is a repetitive series of pairs of notes designated couplets. Whereas the first and second parts of the pattern were invariable throughout the series of 22 songs, the number of couplets in part 3 varied from 4 to 6.

The three-part structure of the pattern 1 song is common to all the patterns of Bewick Wren songs recorded and analyzed by the author. It is particularly striking that the repetitive, couplet construction of part 3 has been observed to occur in all of them. However, the detailed nature of the couplets varies from one pattern to another. Part 3 is the loudest part of the song and consequently has the greatest carrying power in the field. It is the field mark by which the song of the Bewick Wren is identified by the author, not only because it is often the only part heard but also because of its distinctive nature. To the ear the couplets sound like single notes and have an assertive, emphatic quality which can be attributed, at least in part, to their double structure.

Measurements were made of the lengths of the 22 pattern 1 songs and of the inter-

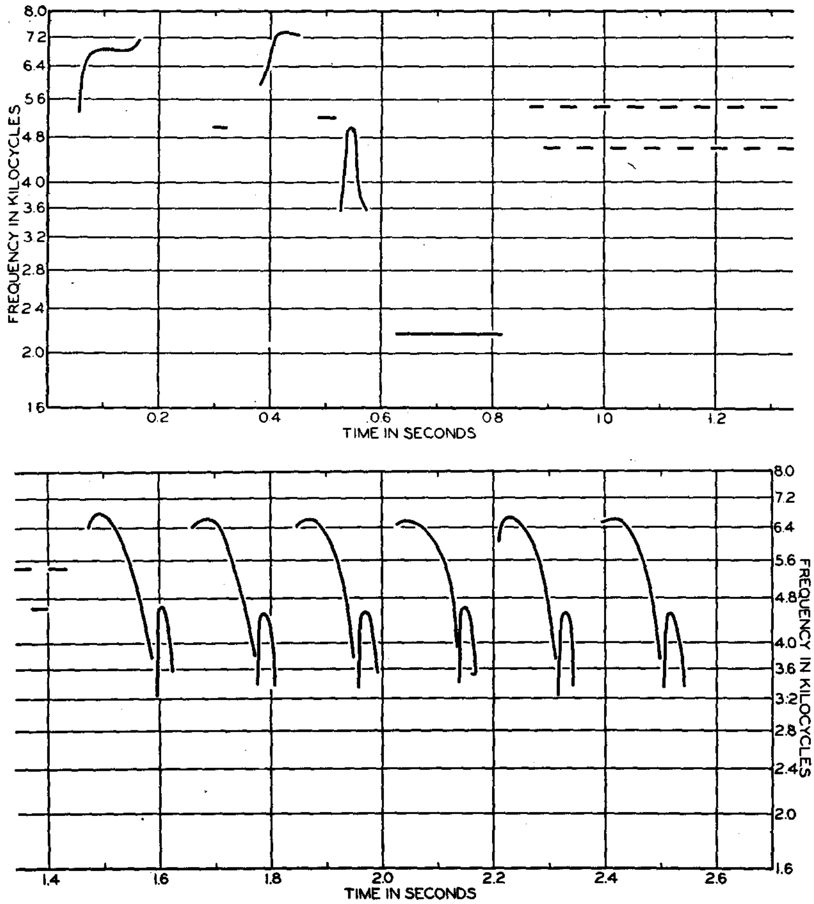

Fig. 6. Frequency-time chart of the representative example of pattern 1 of the Bewick Wren song.

vals between the songs. As described earlier, the half-speed tracings were used in conjunction with the time calibration tracing. Measurements to the nearest 0.01 second can be made by this method. Table 1 summarizes the data on the lengths of the songs. It is apparent from these values that the greatest contribution to the variation in length of the songs arises from the number of couplets present in the song. The average length of the intervals between the songs was 4.48±1.45 seconds. The magnitude of the standard deviation, compared with those calculated for the lengths of the songs, indicates a much greater variation in the length of the intervals, which ranged from 2.98 to 8.80 seconds. From the values for the average length of the songs and for the average length of the intervals the average singing rate was calculated to be 8.7 songs per minute.

Table 1

Lengths of Pattern 1 Songs

	Range (sec.)	Average (sec.)
All songs (22)	2.04–2.57	2.39±0.15
2 Songs containing 4 couplets	2.04–2.13	2.08
7 Songs containing 5 couplets	2.13–2.40	2.30±0.09
13 Songs containing 6 couplets	2.41–2.57	2.49±0.05

SUMMARY

By the use of an assembly of commercially available instruments a new method for the objective study of bird song is provided. Bird songs recorded on magnetic tape are reproduced into a frequency meter and inked oscillograph tracings are obtained by means of a direct inking magnetic oscillograph. The operation and calibration of the equipment and the interpretation of the tracings are discussed. The method is illustrated by the analysis of 22 recorded songs of the Bewick Wren. This analysis shows that all the songs are of the same pattern, a typical specimen of which is depicted in a plot of frequency and time data. The three-part structure of the pattern is discussed and average values presented for the lengths of the songs, the lengths of the intervals between songs, and the singing rate.

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