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SOUND SPECTROGRAPHIC ANALYSIS: SUGGESTIONS FOR FACILITATING AUDITORY IMAGERY

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During the last thirty years the rapid advances in the study of acoustic communication in animals have been largely due to the use of the sound spectrograph for analysis. It has the capacity for simultaneously analyzing three parameters of sound: frequency, time and relative loudness; because the frequency analysis is spectral, tonal quality or timbre can also be deduced. These visual displays of sound patterns have enabled students of bio-acoustics to communicate their results in a concise and objective form. Although manufacturers of the instrument have introduced refinements and new facilities that allow increased flexibility of the analytical process, users have maintained a conservative approach and "sonagrams" (as the makers of the Kay Sona-Graph term the sound spectrograms produced by their instrument) are usually published today in the same format as those twenty to thirty years ago.

In a recent paper J. T. Marshall, Jr. (1977) complained with justification that researchers do not avail themselves of "the small inexpensive device that automatically makes a logarithmic display." Earlier, he pointed out that the human ear and, so far as is presently known, the avian ear respond to pitch, not frequency (Marshall 1964). He therefore took the trouble to convert linear frequency scale analyses to logarithmic scale diagrams in order to make his illustrations more intelligible. At that time the facility for simple conversion from linear to log scale had not been built into most analyzing instruments.

I sympathize with Marshall and would suggest further reforms to meet particular requirements. The most widely published type of sonagram, made with a wide-band filter (300 Hz) and a linear scale, is often incomprehensible to readers who wish to obtain not only information but also good auditory imagery from reading the diagrams. Furthermore, so much detail may be lost in processing and size reduction that some published illustrations are of doubtful value both for identifying species by voice and for distinguishing the elements of a species' vocal repertoire in order to relate them to their behavioral functions.

I find it disquieting that auditory stimuli are often discussed in visual terms, for example, vertical and horizontal lines and streaks, chevrons, zigzags and various shapes. This may be due to the difficulty of imagining sound patterns as such when looking at unfamiliar sonagrams. The capacity for mental rehearsal and the memorizing of sound patterns is essential for researchers in acoustic communication. It should, I think, be developed and fostered rather than allowed to atrophy through constant translation from sound form to visual form, even though the latter is indispensable for publication purposes.

Marshall (1977) claimed that when the log scale is used and if a bird's tones are pure (that is, when the sound pattern comprises tones as distinct from noises), a violinist can read a sonagram and "play the theme on his instrument." I have some reservations about a violinist's ability to read the precise pitches, even given a narrow-band (45 Hz) filter and a log scale; moreover, proportionate, as distinct from symbolic, time representation is notoriously difficult to reproduce with accuracy. Nevertheless, a violinist who makes the attempt will undoubtedly have a better idea of what the bird sang than will most of those readers who simply look at the sonagram.

The resistance of some bio-acousticians to the attempted reproduction of some bird songs on a suitable musical instrument is obstructive, for even an approximate rendition will help in the learning of pitch and time intervals. The purist view that what represents, or is intended for, performance on one type of instrument should not be reproduced on another is invalid. Composers and conductors can, respectively, write or learn orchestral scores of great complexity without recourse to an orchestra. Both may take their scores to a piano and reproduce them thereon, albeit lacking the contrasts in the tonal qualities of different groups of instruments. Tonal quality —or timbre—is not a prerequisite of reproduction, so even if the particular timbre of an avian voice is lost, I see little reason why the pitch, time and loudness relationships should not be made more accessible to reproduction on an instrument. Transcription of a sound pattern from one sound medium to another is surely less reprehensible than consigning it to silence or to the uncertainties inherent in

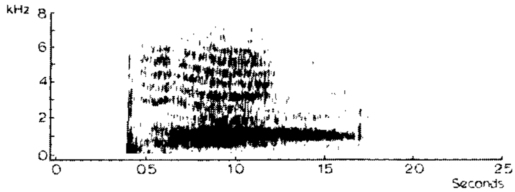

FIGURE 1. White noise illustrated by the aggressive hiss of the Mute Swan.

transformation from the auditory to the visual mode.

The following suggestions are made, therefore, to encourage the production of sound spectrograms which, while maintaining the objectivity of the analytical process, are (1) presented in a form more accessible to the auditory imagery of readers and (2) comprehensible in musical terms and, in some instances, susceptible to performance on a musical instrument.

DEFINITIONS

Units comprising the vocalizations of birds run the gamut of sound from white noise [e.g., the aggressive hiss of the Mute Swan (*Cygnus olor*; Fig. 1)], to extreme purity of tone and constancy of pitch [e.g., the notes of the Musician Wren (*Cyphorhinus aradus*; Figs. 2a and 2b)]. Roederer (1975) described the characteristics of noise, stating that "Any non-periodic pressure oscillation leads to a noise sensation." The Shorter Oxford English Dictionary (S.O.E.D.) defines a tone: "A sound of definite pitch and character produced by regular vibrations of a sounding body; a musical note." The American Standard Acoustical Terminology adopted by the American Standards Association in 1951 (see

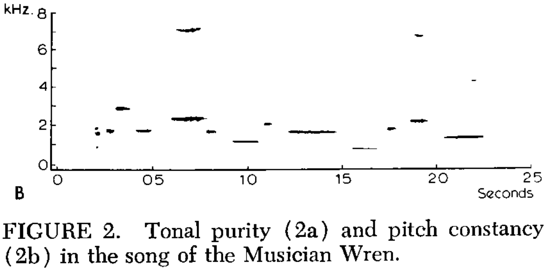

FIGURE 2. Tonal purity (2a) and pitch constancy (2b) in the song of the Musician Wren.

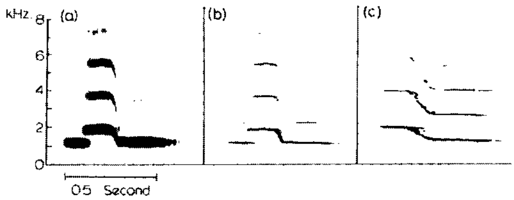

FIGURE 3. Portamento tones. 3a and 3b are wide and narrow band analyses of a duet of the Tropical Boubou. 3c shows a violinist's portamento in narrow band analysis.

Grove 1961) asserted that a "note" shall be defined as the "symbol indicating a tone sensation, the sensation itself, or the vibration causing the sensation." Since this paper is not concerned with the symbolic representation of tones (although it does contain some comments on the symbolic representation of time and relative loudness), I will use the term "tone" generally when referring to any steady-state sound of discernible pitch and to those tones variously described as "portamento" and "glissando" when these latter have the essential property of vibratory regularity as defined by the S.O.E.D. "Portamento" means gliding through all frequencies from f1 . . . . . . fn; it is used as readily by human string players, singers and others as by birds (Fig. 3; for excellent illustrations see Seashore 1938). The word "note" will be substituted for "tone" when there is any likelihood of ambiguity between a tone as already defined and the interval of a whole tone when it is used to describe the pitch relationship.

Surprisingly, Thielcke (1976) refused to use the word "tone" when discussing bird songs and claimed that bird sounds "are almost always discordant combinations that fluctuate in pitch." But one could list innumerable avian sounds which evince a tonal purity rarely attained by musical instruments (e.g., Figs. 2, 9 and 10) and which lack the incidental noise peculiar to most instruments (Figs. 4a and 4b). Fluctuation in pitch, when regular (frequency modulation) is the vibrato of the human singer, string player and skilled wind instrumentalist. Avian vibrato is usually much faster than human vibrato—probably matching the faster temporal resolution of birds (Fig. 5), but it may be produced at the same rate and range as in man (Figs. 6a and 6b). The range of a bird vibrato may be very wide, in which case the purity of tone is lost and a buzzing sound ensues; but with a limited range the sound is not heard as a "discordant combination" but as a tone of particular timbre. Marler (1969) discussed this with great clarity. As noted above,

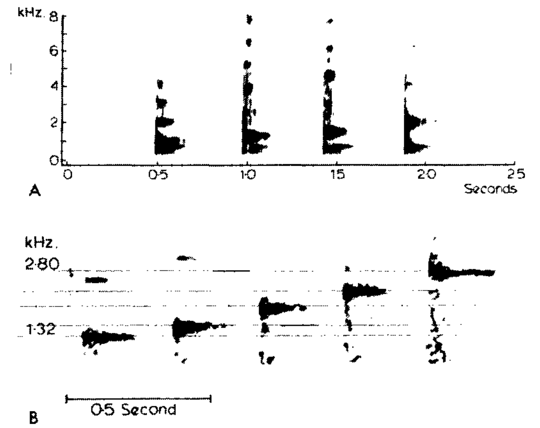

FIGURE 4. Incidental noise accompanying piano tones. 4a wide band analysis; 4b narrow band analysis and magnified frequency scale with preset limits about 400 to 4000 Hz.

musical instruments produce incidental noise; some instruments—particularly those of a percussive nature—give no discernible pitch; and the consonants of sung words are noise. Hence we must accept that much of what we traditionally call "music" does not comprise tones of great purity while much bird vocalization does.

INSTRUMENTATION

The sound spectrograph illustrates both tones and noise with precision. The model used for this study is a Kay Sona-Graph 6061B with facilities for giving both log and linear scales. An interchangeable module, the Sona-Counter 6079A is also used; this incorporates a scale magnifier and a digital frequency counter. The counter displays frequencies within any preset range from 80 Hz to 16 kHz; it has three digits and measures frequency in Hz, or in kHz to one or two decimal places. Horizontal guide lines may be inserted at any required frequencies by means of a push button. It is, therefore, a simple process to make a sonagram meaningful in terms of pitch relationships, but it is essential to have a table

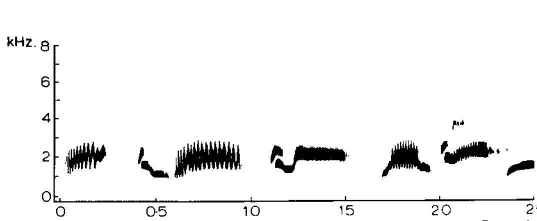

FIGURE 5. Frequency modulation in the song of the Blackbird. Modulation rates: units 1 and 3 about 40 per s; unit 4 about 100 per s and unit 5 about 70 per s.

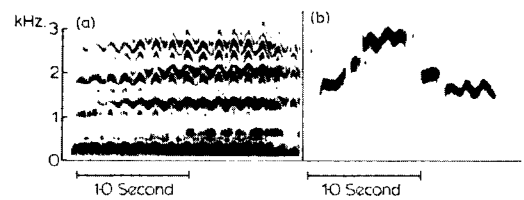

FIGURE 6. Frequency modulation by a human singer (6a) and by a Blackbird (6b), units 3 and 5. The modulation rate is about 6 per s in both.

of frequencies (Table 1) at hand because the digital counter moves rapidly, especially at low magnification levels, and some practice is required to insert the frequency lines with accuracy. The 6061B has three calibration tones: 50 Hz, 500 Hz and 1 kHz; insertion of the 500 Hz tone before the recorded signal is helpful because this requires no subsequent manipulation and provides a criterion for accuracy.

MUSICAL NOTATION

The traditional musical stave is basically a graph with a logarithmic vertical scale so that each octave is equidistant. The great stave, which is preceded by both treble and bass clefs, is necessary only for instruments of wide range. It has little application for illustrating bird songs because the bass stave is used generally—although not exclusively—for frequencies of about 260 Hz and below. The letters A to G are used in alphabetical order to describe pitches; their disposition and repetition are illustrated in Figure 7. Those notes above and below the stave are placed

TABLE 1. A table of frequencies used for inserting the guide lines in Figures 8 and 9. The frequencies of the five lines of the treble stave—transposed up two octaves—are underlined; the remaining frequencies are those of the intervening semitones.

Note names	kHz		
E	1.32	2.64	5.27
F	1.40	2.79	5.59
F♯	1.48	2.95	5.90
G	1.57	3.14	6.27
G♯	1.66	3.32	6.65
A	1.76	3.52	7.04
A♯	1.87	3.73	7.46
B	1.98	3.95	7.90
C	2.09	4.19	8.37
C♯	2.22	4.43	8.86
D	2.35	4.70	9.40
D♯	2.49	4.98	9.95
E	2.64	5.27	10.5
F	2.79	5.59	11.2

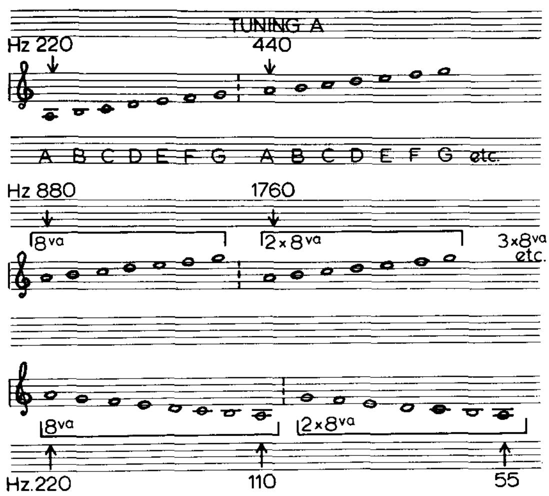

FIGURE 7. The nomenclature and disposition of notes on a musical stave with a treble clef. Transposition up or down by one and two octaves is indicated by 8^{va} and 2×8^{va}.

on, above, or below "ledger" lines: short horizontal lines used to extend the compass of the stave. In theory there is no limit to the number of ledger lines placed above or below one another, but in practice many stacked ledger lines make for difficult reading.

Uncertainties of pitch remain because the Western musical system divides the octave into twelve semitones while the nomenclature, A to G, provides only seven letter names (Fig. 7). In musical notation the use of any or all of the five remaining notes (the black keys of a piano) is shown by a key signature at the beginning of each stave or by inflecting notes with accidentals: the sharp (♯) and flat (♭) raise and lower respectively the pitch of a note by a semitone; the natural (♮) cancels prior instructions to sharpen or flatten a note.

Dividing the frequency spectrum into octaves with their simple 2:1 ratio is universal and presents no problems, but sub-dividing the octave into semitones is less straightforward. The two principal tuning systems, just intonation and equal temperament, have been described and compared with respect to their applicability to bird songs (Hall-Craggs and Thorpe 1972); briefly, the semitone intervals comprising a justly intoned octave have frequency numbers which are derived from the lower integers of the harmonic series (see Olson 1952 for a detailed and lucid explanation). Equal temperament divides the octave into twelve exactly equal semitones, the frequencies of which are obtained by constant multiplication by $1.06 = {}^{12}\sqrt{2:1}$. The stave lines of the illustrations in this paper conform to the frequencies of equal temperament when tuning A = 440 Hz; arithmetical calculations are simpler than those necessitated by just intonation and there is the added advantage that it is usual to sub-divide each equally tempered semitone into 100 cents (1200 cents to the octave) for greater precision of measurement.

EXPRESSING FREQUENCY/PITCH

METHOD

It is a simple process to make a sound spectrogram meaningful in terms of pitch relationships equivalent to those of a five-line stave with a preceding treble clef (𝄞):

(1) Set the frequency scale to logarithmic. (2) Select the narrow band. (3) Preset the range on the scale magnifier to that of the material to be analyzed. (4) Record the signal. Have the table of frequencies at hand and, while the sonagram is being made, insert frequency lines equivalent to those which constitute a treble stave.

Most bird songs are above the range illus-

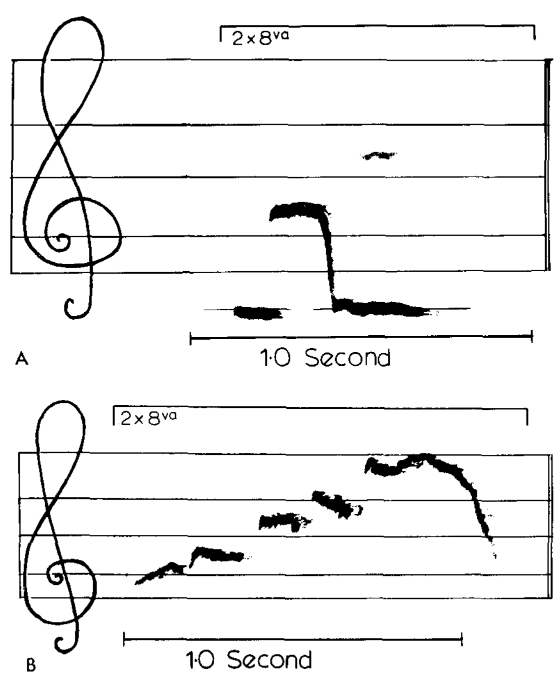

FIGURE 8. Tropical Boubou duet (8a) and song phrase of a Blackbird (8b) analyzed with log scale and frequency scale magnifier. Frequency lines, inserted by using the digital counter, are equivalent to the five lines of a treble stave transposed up two octaves.

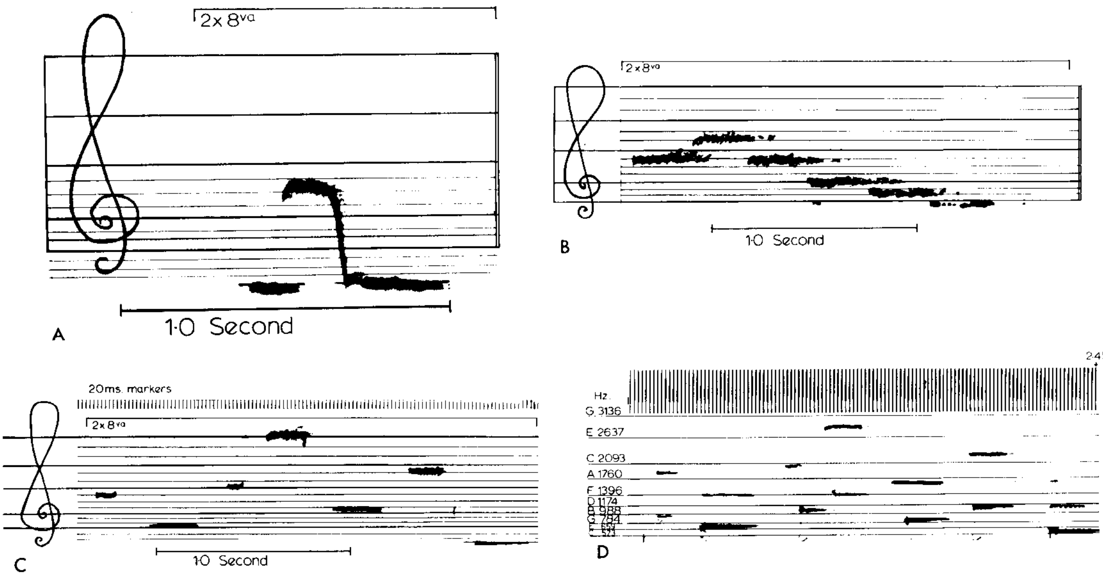

FIGURE 9. The musical stave made by the sound spectrograph as in Figure 8 with the addition of lines inserted at semitone intervals between the traditional five lines. Tropical Boubou duet (9a); song phrase of the Blue-shouldered Robin-Chat (9b); song phrase of the Musician Wren (9c). In Figure 9d the phrase shown in 9c is accompanied by the same melodic line played on a piano but one octave lower; the scale is linear. Figures 9c and 9d have 20 ms markers at top.

trated by the treble stave so it is usually necessary to indicate on the finished sonagram the number of octaves to be transposed. The method is shown in Figure 7, 8^{va} meaning "read as if, or play, one octave higher," 2×8^{va} for two octaves higher and so on. Similar indications can be placed below the stave for downward transposition by octaves. If one then imagines, or inserts, a treble clef at the beginning of the sonagram, it is possible to 'think' the approximate pitch relationships or play them on an instrument (Figs. 8a and 8b). It would be unrealistic to tamper with the pattern on a sonagram by writing in accidentals to show the missing semitones, but this problem is easily overcome by inserting additional guide lines at each semitone interval and subsequently slightly thickening the five original lines for ease in reading (Figs. 9a to 9c).

EXAMPLES

Figures 8a and 8b are examples of simple five-line notation produced by the sound spectrograph. Figure 8a shows a duet by Tropical Boubous (*Laniarius ferrugineus aethiopicus*) whereon the frequency line 1.05 kHz was inserted and then, in part, painted out to leave only the required ledger lines. Figure 8b shows a phrase from the repertoire of a Blackbird (*Turdus merula*); even without the semitone guide lines it may be seen that the bird sang an approximation to the pentatonic scale: G, A, C, D, E. Three examples of staves with semitone indications are shown in Figure 9. Figure 9a shows the duet as in Figure 8a; here the value of the additional lines is illustrated for it is immediately apparent that the initial C is flat while the upper note is, for the greater part, about a quarter tone sharp of the note A. Figure 9b is a song phrase of a Blue-shouldered Robin-Chat (*Cossypha cyanocampter*); this is another example of a pentatonic scale (reading from the lowest note upwards: E♭, F, G, B♭, C) where each note displays a pitch constancy which far exceeds that of the Blackbird phrase in Figure 8b. Figure 9c is another example of the tonal purity of the Musician Wren; Figure 9d shows the same song phrase (upper line of notes) when the sonagram was made with a linear scale and about half the scale magnification of that used for Figure 9c. The frequencies of the guide lines are shown at left, and 20 ms markers are at the top of the graph. The lower line of notes on Figure 9d was played on a piano with, but one octave lower than, the bird's recorded song and a recording was made of the two together. The musicality of the bird's voice is demonstrated, indeed the bird's purity of tone may exceed that of the piano and of course it does not have the accompanying incidental noise peculiar to piano tones. This noise shows up more clearly on the original sonagram (cf. Fig. 4b) but

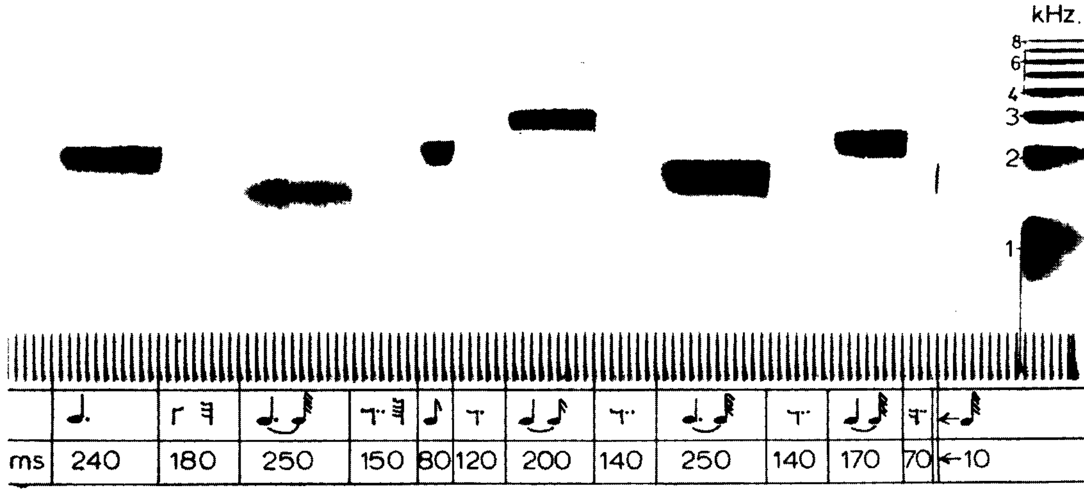

FIGURE 10. Song phrase of the Musician Wren; wide-band analysis. The log scale at right given by 1 kHz calibration tone. 20 ms markers replace the base line, and time symbols and their equivalents in milliseconds are shown below.

some of the marking has been lost in processing.

EXPRESSING TIME

The 50 Hz calibration tone on the Kay 6061B is an excellent time indicator, giving 20 ms divisions which may either replace the base line or be positioned above the diagram (Figs. 9c, 9d and 10). For general use it is more convenient to make a time scale in this way for placing on sonagrams; it is then possible to measure accurately to about 10 ms. Slowing the playback speed of the signal to be fed to the analyzer will increase precision to 5 ms or less but, unless a recording has been made in conditions which preclude reflected sound, it is often difficult to determine the exact termination of each discrete sound unit. For this reason it is probably safer to accept a margin of error of ±5 ms when measuring time relationships on an ordinary 2.4-s sound spectrogram.

The desirability of reproducing in musical notation the time patterns shown on sonagrams depends upon the user. It is easy enough to learn to read a (usually) single line of pitches in the musical context, because the spatial relationships at least resemble the pitch relationships. The time symbols of music bear no physical resemblance to the durations and durational relationships they represent; but since it is sometimes claimed that the time patterning of bird vocalizations cannot be reproduced accurately in this form, I wish to demonstrate that it can. That birds do not sing in "bars" of equal and prescribed duration with regularly recurring strong and weak "beats" is irrelevant; much human music is not metrical.

A simple procedure, perhaps the only one, is to make a wide-band sound spectrogram and measure the duration of the shortest sound unit, or silence between two units, whichever is less, and equate this with a brief time symbol and its equivalent "rest." (A rest shows the duration of silence between two temporally discrete notes.) The choice of a minimum duration symbol could depend upon the range of durations within the pattern to be symbolized, but it is helpful to have a standard table of relationships. In theory it is possible to take 1 ms as the minimum, but for the reasons given above it is more realistic to use a 10 ms minimum. Table 2 gives symbols based upon multiples of 10 ms. The time values of the symbols in columns three and four are obvious but two aspects of the notation may require explanation: a dot placed beside and immediately after a note or rest adds to that symbol one-half of its value, a second dot adds half the value of the first one. A "tie" connecting two notes of the same pitch instructs the reader to add the value of the second note to that of the first; the second note is not played or sung. To some extent dots and ties are interchangeable and when, as in bird songs, one is not bound by the conventions demanded by time signatures, the better choice is that which is easier to read.

Figure 10 is an example of this notation placed below the original sonagram. For the purpose of measurement it is quicker and easier to place the time scale on the sonagram

TABLE 2. Time symbols and their equivalents in ms.

RELATIVE NOTE VALUES	ms	NOTE SYMBOL	REST SYMBOL	ms	NOTE SYMBOL	REST SYMBOL	ms	NOTE SYMBOL	REST SYMBOL
1/64	10	𝅘𝅥𝅲	𝅁	+5 (15)	𝅘𝅥𝅲.	𝅁.			
1/32	20	𝅘𝅥𝅱	𝅀	+10 (30)	𝅘𝅥𝅱.	𝅀.			
1/16	40	𝅘𝅥𝅰	𝄿	+20 (60)	𝅘𝅥𝅰.	𝄿.	+10 (70)	𝅘𝅥𝅰..	𝄿..
1/8	80	𝅘𝅥𝅯	𝄾	+40 (120)	𝅘𝅥𝅯.	𝄾.	+20 (140)	𝅘𝅥𝅯..	𝄾..
1/4	160	𝅘𝅥	𝄽	+80 (240)	𝅘𝅥.	𝄽.	+40 (280)	𝅘𝅥..	𝄽..
1/2	320	𝅗𝅥	𝄼	+160 (480)	𝅗𝅥.	𝄼.	+80 (560)	𝅗𝅥..	𝄼..
1	640	𝅝	𝄻	+320 (960)	𝅝.	𝄻.	+160 (1120)	𝅝..	𝄻..

Tied notes are used for any multiples of 10 that are not included in this table e.g. 𝅘𝅥‿𝅘𝅥𝅱. = 190 ms; 𝅗𝅥‿𝅘𝅥𝅰‿𝅘𝅥𝅲 = 370 ms. Ties may also be used in place of dots e.g. 𝅘𝅥‿𝅘𝅥𝅯‿𝅘𝅥𝅰 = 280 ms. Rests used consecutively are not tied together.

and give a list of figures which can then be compared with other relevant lists. But in order to obtain an auditory image of the time pattern, the symbolic version is probably essential. Kurt Stone (*in* Cole 1974) pointed out the fundamental disadvantages of proportionate notation: "Human beings simply do not seem to possess a space perception equal in acuity to their pulse perception: if they are not given something they can count, they will not be able to play in time." This remains true if the word "think" is substituted for the word "play." Support for Stone's contention is to be found in the evolution of musical notation, a process that resembles biological evolution in that "natural selection" operates and "deleterious mutations" in the form of personal idiosyncracies die out. Through this process pitch became, and has remained, tied to spatial relationships, while time indications have developed in symbolic form with increasing precision in the selection and use of the symbols. Attempts to introduce proportionate notation are short-lived.

When reading a sound spectrogram it is difficult to discern a 10 ms, or even 20 ms, difference in the duration of units even when they are adjacent to one another and of similar structure and frequency. However, even a 10 ms difference is immediately apparent when illustrated symbolically—unit 1 = 240 ms, units 2 and 5 = 250 ms (Fig. 10). I do not suggest that pitch/time symbols should replace the pattern as shown on a sonagram, for too many valuable attributes of the pattern would be lost. But for those who wish to hear the pattern, if only in imagination, the appropriate symbols placed beneath the diagram are a decided aid.

EXPRESSING RELATIVE LOUDNESS

Unless a sound spectrogram is made with a sound pressure level curve above the frequency/time trace, relative loudness is shown only by the density of the marking. Mark density is informative when examining an original, but the information is lost when the graph is printed as a black-and-white illustration. For good measurement of relative loudness, a sound pressure level curve must be added or, better still, amplitude sections must be made; but for the all-purpose sonagram reproduced in black-and-white, the sparing use of symbols, as advocated by Hold (1970), is helpful. Musical symbolism of dynamic range is relative to context but it is compelling in its graphic simplicity. If the delicate shading of a sound spectrogram is to be lost in print, it seems sensible to redress some of the loss by placing a few easily understood symbols beneath the base line. These are as follows:

(1) Gradually increasing in loudness

cresc.

(2) Gradually decreasing in loudness

decresc.

(3) A stressed or accented note ∧ > is the more usual symbol but it is apt to be confused with a short decrescendo symbol, as in (2) above, unless the context is quite clear.

(4) Loud	*f*	(forte)
(5) Quiet	*p*	(piano)
(6) Fairly loud	*mf*	(mezzo forte)
(7) Fairly quiet	*mp*	(mezzo piano)

The symbols "f" (4) and "p" (5) can be multiplied to indicate extremes (fortissimo

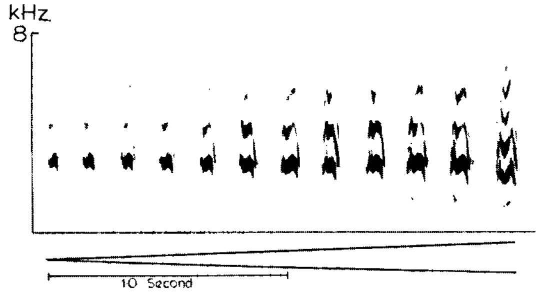

FIGURE 11. "Wickering" calls of the Marsh Harrier with gradual increase in loudness.

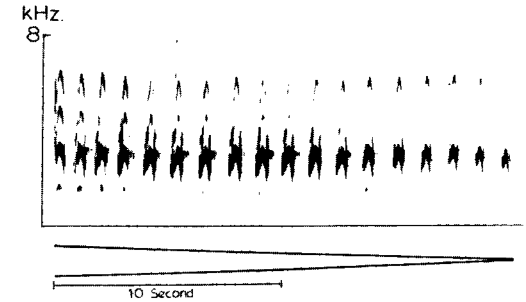

FIGURE 12. "Wickering" calls of the Hen Harrier with gradual decrease in loudness.

and pianissimo), although the use of more than "fff" and "ppp" is unusual in music.

Figures 11 and 12 show bouts of "wickering" calls of the Marsh Harrier (*Circus aeruginosus*) and the Hen-Harrier (*C. cyaneus*) respectively. Inserting symbols (1) and (2) helps to inform the reader that there is an overall increase of loudness in the calling bout of the former while the reverse is true of the latter. Changes in band width and unit duration are more apparent than real, especially if the delicate shading of the sound spectrogram is lost in printing. [See Thompson, p. 220.]

SUMMARY

Users of the sound spectrograph seem rarely to avail themselves of the refinements and new facilities introduced by manufacturers. By using a scale magnifier, frequency counter and log scale, sound spectrograms can be made to resemble simple musical notation in the pitch domain without forfeiting the strict objectivity of the analytical process. It is suggested that such sound spectrograms facilitate auditory imagery and, at the same time, help non-specialists to a better understanding of published illustrations. There is a brief discussion of the relative merits of proportionate versus symbolic time representation, and a proposal that the addition of symbols illustrating relative loudness would help to restore information lost through reproduction.

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