Short Communication

Artificial Neural Network Trained to Identify Mosquitoes in Flight

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KEY WORDS: wingbeat frequency; insect flight monitor; artificial neural network; Culicidae; *Aedes aegypti*; *Aedes triseriatus*.

Interspecific and intraspecific differences in wingbeat frequencies have been used to identify insects in flight (Reed *et al.*, 1942; Sotavalta, 1947; Sawedal and Hall, 1979; Greenbank *et al.*, 1980; Farmery, 1982; Riley *et al.*, 1983; Schaefer and Bent, 1984; Unwin and Corbet, 1984; Rose *et al.*, 1985). Spectral analyses of insect wingbeat recordings typically reveal a harmonic series with the wingbeat frequency as the fundamental. Moore *et al.* (1986) suggested that automated instrumentation could be designed to discriminate among species of flying insects by recognizing spectral patterns formed by these harmonics, analogous to the way in which the human ear and brain discriminate among musical instruments by recognizing patterns of harmonics in sounds they make.

To test this idea, wingbeat frequencies were recorded for two sets of independently reared mosquitoes, a "training set" and a "test set," each set consisting of four groups of insects: *Aedes aegypti* (L.) females and males and *A. triseriatus* (Say) females and males. The objective was to identify the species and sex of individuals in the test set with discriminant functions calculated using spectral characteristics extracted from recordings of insects in the test set.

Following is a brief description of the experimental methods. Details are given in the original paper (Moore *et al.*, 1986). A photosensor (Unwin and Ellington, 1979) was used to detect fluctuations in light intensity caused by reflections off individual mosquitoes flying through a light beam. Digital recordings of the signals were made with a microcomputer (IBM PC) equipped with an analog-to-digital converter (LabTender, Tecmar Inc., Solon, OH) under the control of a program which simulates a digital oscilloscope (SCOPE2, Moore

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Scientific, Kula, HI). A change in light intensity caused by a mosquito flying in front of the sensor triggered storage of 512 samples at a rate of 10 kHz (Fig. 1A). Each signal was converted to a 256-cell frequency spectrum (Fig. 1B) using the fast Fourier transform (Cooper, 1981).

Wingbeat frequency and amplitudes of the first four harmonics were extracted from each signal in the training set (n = 300; approximately 75 signals for each species–sex combination). Discriminant functions based on several combinations of these variables were calculated and were tested by using them to identify signals from the test set (n = 60; approximately 15 signals for each species–sex combination). The function based on wingbeat frequency alone identified the correct species and sex 84% of the time. Accuracy did not improve when the amplitudes of the harmonics were used in the calculations. Thus, it was concluded that the spectra contained little or no information in addition to the wingbeat frequency which is useful for insect identification. However, more recent analysis of data from this experiment using an artificial neural network (ANN) indicates that there is additional information contained in the frequency spectrum.

ANNs are a recent innovation from the field of artificial intelligence (Stan-

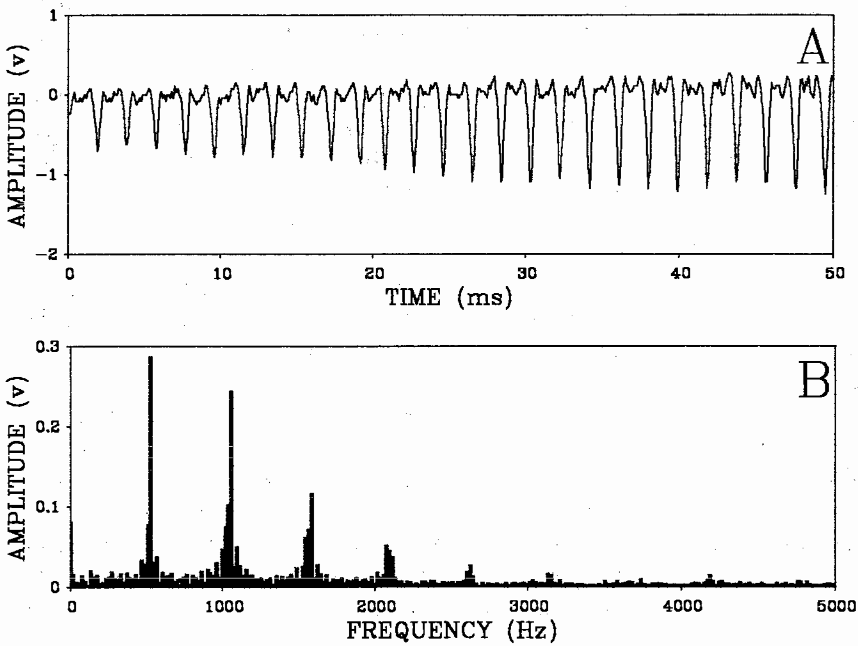

Fig. 1. (A) Signal produced by the flight movements of a female *Aedes aegypti* mosquito. (B) Frequency spectrum.

Table I. Output from an Artificial Neural Network Trained to Differentiate Among Four Groups of Mosquitoes

True identity	Network trained with full spectrum					Network trained with wingbeat frequency only				
	Output neuron excitation[a]					Output neuron excitation				
	AEF	AEM	ATF	ATM	Network ID[b]	AEF	AEM	ATF	ATM	Network ID
Aedes aegypti female	90 (10)	0 (0)	0 (0)	0 (0)	+	81 (19)	0 (0)	0 (0)	99 (99)	?
	99 (1)	0 (0)	0 (0)	0 (0)	+	99 (1)	0 (0)	2 (2)	1 (1)	+
	89 (11)	0 (0)	0 (0)	0 (0)	?	97 (3)	0 (0)	0 (0)	55 (55)	?
	99 (1)	0 (0)	0 (0)	0 (0)	+	97 (3)	0 (0)	0 (0)	55 (55)	?
	99 (1)	0 (0)	0 (0)	0 (0)	+	99 (1)	0 (0)	2 (2)	1 (1)	+
Aedes aegypti male	2 (2)	1 (99)	0 (0)	3 (3)	?	99 (99)	0 (100)	0 (0)	4 (4)	X
	0 (0)	99 (1)	0 (0)	0 (0)	+	0 (0)	99 (1)	0 (0)	0 0	+
	0 (0)	90 (10)	1 (1)	0 (0)	+	0 (0)	95 (5)	2 (2)	0 0	+
	0 (0)	98 (2)	0 (0)	0 (0)	+	0 (0)	99 (1)	1 (1)	0 0	+
	0 (0)	95 (5)	0 (0)	0 (0)	+	0 (0)	88 (12)	1 (1)	15 (15)	?
Aedes triseriatus female	0 (0)	0 (0)	99 (1)	0 (0)	+	0 (0)	0 (0)	99 (1)	0 (0)	+
	0 (0)	0 (0)	99 (1)	0 (0)	+	0 (0)	1 (1)	99 (1)	1 (1)	+
	0 (0)	0 (0)	99 (1)	0 (0)	+	0 (0)	0 (0)	99 (1)	0 0	+
	0 (0)	0 (0)	99 (1)	0 (0)	+	0 (0)	0 (0)	99 (1)	0 0	+
	0 (0)	0 (0)	59 (41)	1 (1)	?	0 (0)	1 (1)	99 (1)	1 (1)	+
Aedes triseriatus male	0 (0)	0 (0)	2 (2)	99 (1)	+	0 (0)	0 (0)	3 (3)	99 (1)	+
	0 (0)	0 (0)	0 (0)	46 (54)	?	0 (0)	0 (0)	2 (2)	90 (10)	+
	0 (0)	0 (0)	0 (0)	97 (3)	+	8 (8)	0 (0)	2 (2)	90 (10)	+
	0 (0)	0 (0)	0 (0)	99 (1)	+	8 (8)	0 (0)	0 (0)	99 (1)	+
	0 (0)	0 (0)	0 (0)	99 (1)	+	0 (0)	1 (1)	0 (0)	99 (1)	+
	15 (15)	0 (0)	0 (0)	88 (12)	?	9 (9)	0 (0)	0 (0)	98 (2)	+
	89 (89)	0 (0)	0 (0)	0 (100)	?	97 (97)	0 (0)	0 (0)	55 (45)	?
	0 (0)	0 (0)	0 (0)	99 (1)	+	0 (0)	0 (0)	11 ()	99 (1)	+
	0 (0)	0 (0)	0 (0)	99 (1)	+	0 (0)	0 (0)	1 (1)	99 (1)	+

[a] Neuron excitation expressed as a percentage. Values in parentheses are absolute errors (difference between observed and expected neuron excitation).
[b] +, input identified correctly; X, input misidentified; ?, input unidentified. Refer to text for decision criteria.

identified correctly, 5 were unidentified, and 1 was misidentified (Table I). The increased error indicates that the network uses information in addition to the wingbeat frequency. It should be noted that when the wingbeat recordings were made, there was no attempt to control or measure the orientation of mosquito flight paths with respect to the light beam or sensor. It is probable that more consistent spectral signatures can be obtained by controlling angles of reflection.

Even though morphologically similar species were used in the experiment, each signal, lasting only 0.05 s, contained information enabling identification of species and sex with a high degree of confidence. This study demonstrates the feasibility of developing automated instrumentation capable of counting and identifying insects in flight. With further development, this type of instrumentation could become an important tool for research and pest control. Possible applications include continuous monitoring of several sympatric populations (useful for ecological studies, biological control, and integrated pest management), pollination studies, measurement of diurnal activity cycles, and evaluation of attractants and repellents.

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