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TECHNICAL CONTRIBUTION

AN ELECTRONIC ACTIVITY INTEGRATOR FOR OPERANT CONDITIONING OF PATTERNS OF NEURAL AND MUSCULAR ACTIVITY[1]

EBERHARD E. FETZ AND RONALD I. BARENSTEN

Departments of Neurological Surgery and Physiology and Biophysics, and Regional Primate Research Center, University of Washington, Seattle, Wash. 98195 (U.S.A.)

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The following electronic circuit was designed to detect and operantly condition specific patterns of neural and muscular activity in awake monkeys (Fetz and Finocchio 1971; Fetz and Baker 1973; Fetz and Wyler 1973; Wyler and Fetz 1974). These response patterns consist of transient bursts of activities in specific elements (neurons or muscles) and can include the simultaneous suppression of activity in other elements. The circuit allows the required amount of activation or suppression of each element to be continuously and independently controlled by the experimenter, thereby permitting specific response patterns to be differentially reinforced or "shaped".

The basic components of this circuit—called an activity integrator—are diagrammed in Fig. 1, *A*. In its most general form, the integrator has several input channels, each of which accepts a signal voltage (v_i) proportional to the recorded activity of a neuron or muscle. For neural activity, this input signal is a train of rectangular voltage pulses triggered by the action potentials of the cell. For muscle activity, the signal is the electromyogram recorded from the appropriate muscle. Each analog input signal is full-wave rectified and multiplied by a variable weighting factor (a_i) whose sign and magnitude is determined by a polarity and gain control for each channel. The weighted signals are then summed, producing a "Weighted sum voltage" $V(t)$:

$$V(t) = \sum_i a_i |v_i(t)|$$

Thus, the relative amount of activity or inactivity required in each element for reinforcement is specified by the set of weighting factors a_i. This summed voltage is temporally integrated in a leaky parallel RC integrator, producing the "integrator voltage" V (t):

$$\mathrm{V}(t) = \int_{t_0}^{t} V(\eta)\, e^{-(t-\eta)/\tau}\, d\eta$$

where t_0 = time of previous integrator reset; τ = discharge time constant of integrator; η = dummy integration variable.

This integrator voltage approaches the instantaneous summed voltage with a rapid time constant (100K × C; generally 1 msec) and decreases to zero in the absence of activity with a longer time constant τ (usually 50 msec). When the integrator voltage reaches a pre-set reinforcement level (T), a Schmitt trigger produces a pulse which indicates that the required pattern has been emitted. This pulse resets the integrator voltage to zero for an adjustable period (usually set to 0.5 sec but variable between 0.05 and 2 sec), and may also be used to trigger a feeder during reinforcement periods. By appropriately setting the parameters a_i according to the degree of ongoing activity, the integrator voltage can be set to fluctuate at some level below T such that transient changes in the response pattern will drive the integrator voltage to the reinforcement level. As the requisite response patterns are emitted more frequently, the parameters a_i may be modified to require greater response differentiation. Continuous visual feedback is provided by monitoring the integrator voltage with an underdamped zero-center meter in front of the animal. The maximum deflection right is calibrated to correspond to reinforcement level; since the extreme right position of the meter needle consistently corresponds to reinforcement, for all types of schedules, rightward deflections can become secondary reinforcers. This meter is activated and illuminated only during conditioning periods, providing a useful discriminative stimulus for reinforcement. A second meter for the experimenter has also proven useful to monitor the integrator voltage and adjust the parameters. An auditory feedback signal may also be generated by controlling the amplitude or frequency of a tone with the integrator voltage.

The major electronic components of the activity integrator are diagrammed in Fig. 1, *B*. The rectifier circuit for one of the input channels is shown at the top. The input voltage v_1 is coupled through an FET follower (Q1) which establishes a high input impedance and a low output impedance compatible with the low circuit impedances chosen for operational amplifier A1 to maximize bandwidth and minimize leakage. The coupling capacitor between Q1 and A1 eliminates integration of d.c. offsets in the input signals; to integrate signals

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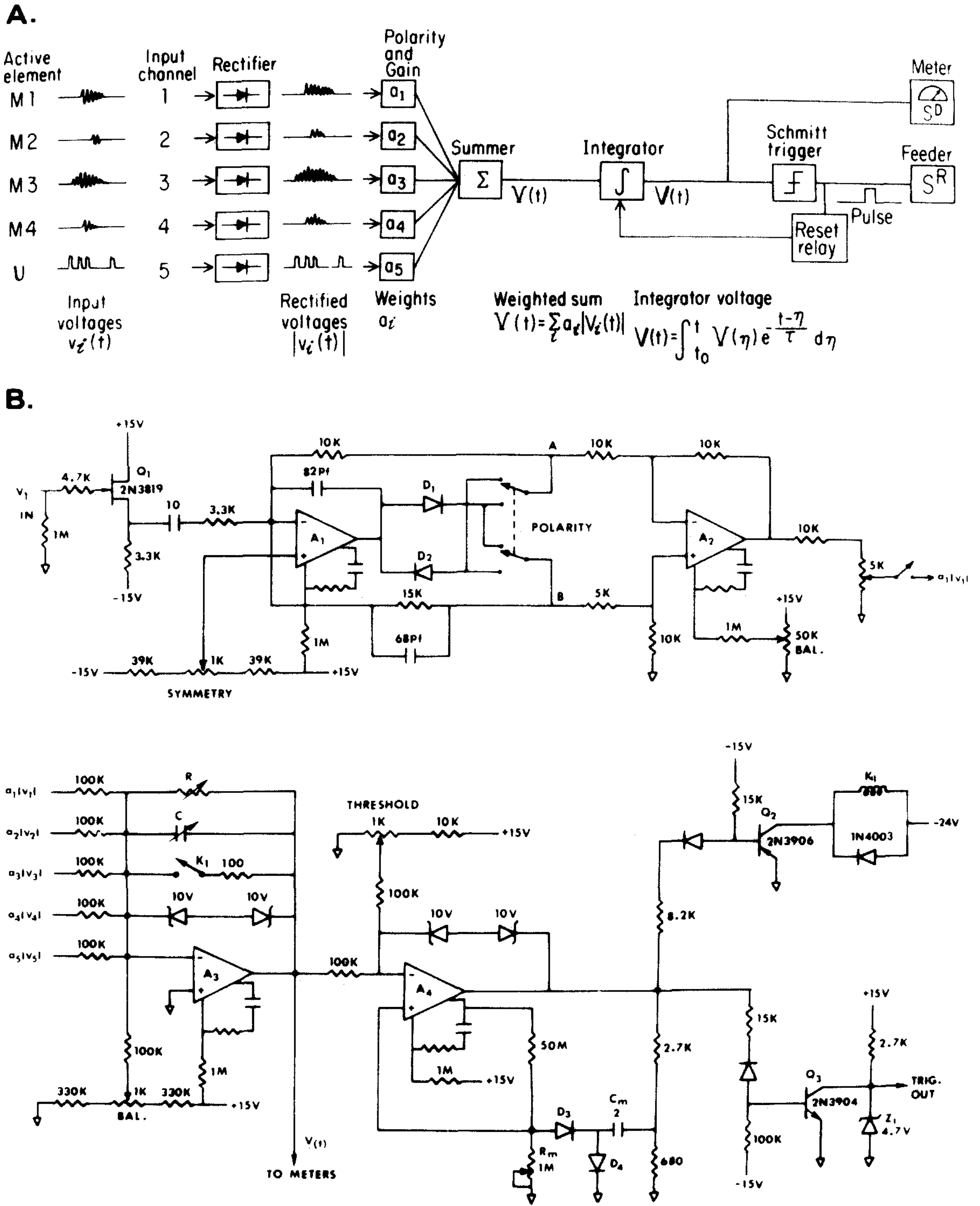

Fig. 1. *A*: Block diagram of major components of activity integrator circuit. Input voltages shown are EMG activity of four muscles (M1....M4) and pulses triggered from one neuron (U). *B*: Specific electronic components of circuit performing functions shown in *A*. The input signal (v_1) is rectified by A1 and A2 (top), summed and integrated by A3; integrator reset is controlled by the comparator circuit associated with A4. All operational amplifiers are Burr Brown 3058/01. The unlabeled compensation networks consist of a 390 Ω resistor in series with a 0.002 mfd capacitor. All diodes are 1N458.

with long d.c. components this capacitor should be sized appropriately. Diodes D1 and D2, each conducting on alternate polarities of an a.c. input signal, become virtually perfect diodes due to the high open-loop gain of A1, thus assuming linear rectification of low-level signals. The half-wave rectified signals appearing at points A and B are converted by operational amplifier A2 to a full-wave rectified signal. Polarity of the output signal can be reversed by switching D1 and D2.

The chosen number of rectified signals is summed and integrated by A3. A variable high resistance (R) in parallel with the integrating capacitor (C) produces a long discharge time constant ($\tau = RC$) with respect to the charging time constant. τ is usually set to 50 msec, but is variable between 0.1 msec and ∞. C is typically 0.01 μf, but variable between 0.001 μf and 10 μf; R is usually 5 Meg, but variable between 100k and ∞. The discharge time constant can be changed without affecting the charging time constant by varying R.

Integrator voltage is reset to zero by contact closure of relay K1. Integrator reset is controlled by comparing the integrator voltage to a threshold reference voltage (set at 1 V). When the integrator voltage reaches reference, Schmitt trigger A4 changes state, closing the reset relay. Positive feedback holds A4 in the reset state until C_m charges through R_m and D3. After a variable charge time set by R_m, A4 returns to its original state, opening the relay and discharging C_m rapidly through D4. Thus the functions of a Schmitt trigger and a monostable multivibrator are combined in one stage. The reset relay is energized by the switching amplifier Q2. A logic pulse is produced by switching amplifier Q3 for which Zener diode Z1 clamps the output to a value compatible with TTL logic.

A variety of response patterns have been reinforced with the activity integrator by using appropriate input voltages and specifying appropriate polarities of their contributions to the integrator voltage: (A) Transient *increases in activity* of a cell or muscle may be reinforced by leading the corresponding signal voltage to a single channel with the gain positive; thus activity in that element drives the integrator voltage (V (t)) to the reinforcement level (T). (B) Transient *decreases in unit activity* may be reinforced by using two input channels. One channel with a positive gain accepts voltage pulses continually generated by an external pulse generator; these pulses drive V (t) toward T; a second channel with negative gain accepts input voltages proportional to activity of the unit, which drive V (t) away from T. Thus, sustained unit activity prevents reinforcement, whereas unit inactivity allows the multivibrator pulses to trigger reinforcement (Fetz and Baker 1973; Fetz and Wyler 1973). (C) *Differential patterns of activity* in two or more elements may be reinforced by feeding signal voltages of the element whose activity should increase into a positive polarity input and signals from the element(s) whose activity should decrease into a negative polarity input. This arrangement has been used to reinforce differentially: (a) firing rates in two simultaneously recorded units (Fetz and Baker 1973); (b) isolated activity in one of four arm muscles with simultaneous suppression of the other three (Fetz and Finocchio 1971); and (c) precentral cortex unit activity with simultaneous muscle suppression (Fetz and Finocchio 1971). (D) Another application has been to reinforce *firing patterns* of epileptic cells which show two modes activity—bursting and regular. Either of these modes may be differentially reinforced by generating separate pulses for spikes occurring in each mode on the basis of interspike interval criteria (Fetz and Wyler 1973). For example, to reinforce differentially regular activity, pulses from spikes occurring with "regular" intervals (greater than 10 msec) were led into a positive polarity input and pulses from spikes occurring with burst intervals (less than 10 msec) were led into a negative polarity input.

Clearly other signal voltages besides activity of cells or muscles may be used as inputs. Specific spectral components of the EEG could also be integrated and differentially reinforced. In general, any variable associated with an operant response, such as force or position, could also be used. One of the most fruitful applications of the activity integrator has been to reinforce differentially the dissociation of two correlated variables in order to test the stability of the correlation (Fetz and Finocchio 1971).

SUMMARY

An activity integrator circuit designed to detect and operantly reinforce patterns of neural and muscular activity is described. An integrator voltage proportional to the weighted sum of multiple input signals reaches a threshold level when the requisite response pattern is emitted. A variety of response patterns may be differentially reinforced, depending on the nature of the integrated signals.

RESUME

INTEGRATEUR ELECTRONIQUE D'ACTIVITE POUR CONDITIONNEMENT OPERANT DE PATTERNS D'ACTIVITE NERVEUSE ET MUSCULAIRE

Les auteurs décrivent un circuit intégrateur d'activité destiné à détecter et à renfocer de façon opérante les patterns d'activité nerveuse et musculaire. Un intégrateur de voltage proportionnel à la somme pondérée des signaux multiples d'entrée atteint son niveau liminaire quand le pattern de réponse demandée est émis. Toute une variété de patterns de réponses peuvent être renforcées de facon différentielle, selon la nature des signaux intégrés.

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