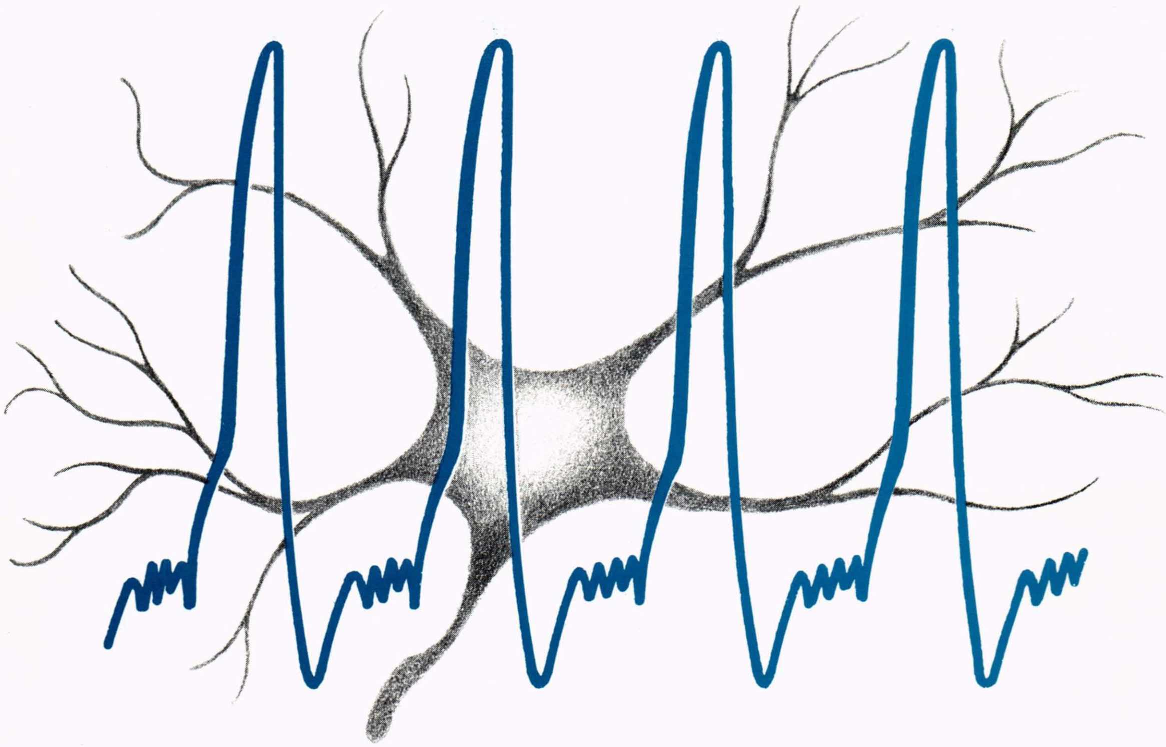

A CORRELATOR OF TIME INTERVALS BETWEEN PULSES

In the field of neurophysiology, analysis of the majority of neuronal data has been a tiresome task. Many questions and hypotheses posed by investigators in the field have remained unanswered and/or unverified because of inadequate analytical tools. For example, in the course of research at APL by F. F. Hiltz*, the need arose for an inexpensive means of ascertaining time relationships between spike discharges (pulses) in neurons. (Equipments that perform similar functions either were not commercially available, were prohibitively expensive, or lacked the ability to do the job.)

To meet this requirement, a small, special-purpose electronic device known as a *correlator* was designed and built. The correlator will supply the user with the following information: (1) a *time-interval histogram,* or the time intervals between adjacent pulses in a pulse train; (2) the number of times any two pulses in the same pulse train are separated by given time delays, or *time interval autocorrelation;* and

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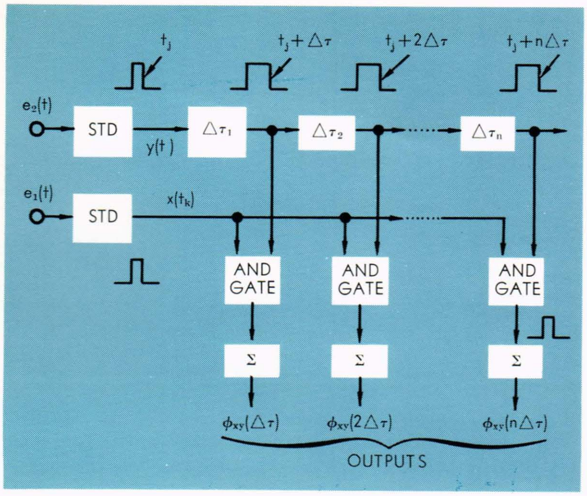

Fig. 1—A simplified block diagram of the APL-designed and built correlator.

(3) the number of pulses in separate pulse trains that are separated by given time delays, or *time interval crosscorrelation.*[1-4] The device may be used either on-line or off-line. It was designed primarily for use with neuronal signals. However, it may be used on other pulse trains where interest is in the time relationships of events exceeding a predetermined threshold. By providing an on-line indication of the time relationships between pulses obtained from a neuron, an investigator could vary his experimental parameters and be provided with an immediate indication of the effects. It may also be used as a guide for future, more detailed analysis.

Using switches and patch panels, the circuitry of the correlator may be connected to provide a wide range of operating parameters and modes. The input signal to be processed is applied to a circuit unit termed a standardizer (STD), whose function is to detect the point at which the input signal has exceeded a predetermined threshold. Upon detection of the threshold crossing, it produces a narrow, rectangular pulse of constant amplitude and width. The STD pulses are used as the inputs for all of the processing circuitry.

[1] V. J. Caggiano, "Pulse Analysis by Histograms," *Instruments and Control Systems,* **34,** Mar. 1961, 498-499.

[2] G. F. Poggio and L. J. Viernstein, "Time Series Analysis of the Discharge Sequences of the Thalamic Somatic Sensory Neurons," *J. Neurophysiol.,* **27,** 1964, p. 517.

[3] F. F. Hiltz and C. T. Pardoe, "A Between Pulses Time-Interval Correlator," *Proc. 3rd National Biomedical Sciences Symposium* (in press).

[4] F. F. Hiltz and C. T. Pardoe, "A Correlator of Time Intervals Between Pulses," *IEEE Trans. on Bio-Medical Engineering,* BME-12, Apr. 1965, 113-120.

A block diagram of the portions of the correlator used for time-interval correlations is shown in Fig. 1. The standardizers are triggered whenever their input signal exceeds the present reference, or threshold, level. Thus, the pulses $y(t_j)$ and $x(t_k)$ correspond in time to the threshold crossings of $e_2(t)$ and $e_1(t)$, respectively. The pulses $x(t_k)$ are used as the time references in the AND gates as shown. The pulses $y(t_j)$, in turn, trigger a pulse delay circuit $\Delta\tau_1$. The trailing edge of this delayed output occurs at time $t_j + \Delta\tau$, and in turn triggers another pulse delay circuit, $\Delta\tau_2$, etc. The delay circuits are relatively simple RC circuits, with one accompanying transistor for isolation.

The reference pulses $x(t_k)$ from the STD and the $\Delta\tau$'s are used as inputs to the coincidence AND gates. Whenever coincidence occurs between the two inputs to a particular AND gate, an output pulse is obtained from that gate.

This pulse indicates that two events in the input signals are separated by a time corresponding to the total delay represented by the particular $\Delta\tau$ used as the input to the coincidence gate. The ouput pulse from the coincidence AND gate is fed to a counter in order to obtain a total count of the number of events separated by that particular time interval. Time-interval crosscorrelation may degenerate into a more particular function, time-interval autocorrelation. To obtain the time-interval autocorrelation, the inputs $e_1(t)$ and $e_2(t)$ to the standardizers are derived from a single signal source rather than from separate ones.

The maximum number of discrete events per unit of time that may be reliably processed in either of the correlation modes is determined by the delay-circuitry duty cycle. If the smallest time delay in the series of Δ_τ circuits is T sec, then the maximum input-event frequency contained in $e_2(t)$ is limited to $1/(2T)$ events per second. The correlator, as it was built for neuronal studies, has a capacity of 448 individual delay circuits that may be connected in various configurations in groups of sixteen. That is, there is one available input lead per 16 delays. Each delay output, however, is available. The individual time delays may be varied from 1 to 20 msec by a simple capacitor change in each delay circuit. To exceed this delay range, other component values must be changed as well. There are 48 coincidence circuits that may be connected to any of the delay circuits.

Readout of the results may be in several forms. There are 16 readout channels that individually produce voltages indicative of the number of coincidences experienced by the AND gates to which they are connected. This form of readout is useful since the time history of correlations, as well as their total number, is available. Another form of readout is in the form of a bar graph, labeled composite readout. The output pulses from each coincidence gate are fed to an integrate-and-hold circuit associated with that particular coincidence gate. Each such circuit is, in turn, sampled by an electronic switch. Thus, a voltage indicating the number of pulses associated with each of the 48 time delays being monitored is available as a composite output. This voltage may then be displayed in bar-graph form on an oscilloscope (Figs. 2 and 3).

The correlator has been extensively tested with various test pulse trains having known characteristics. It has also been used on-line during neuronal simulation studies, as well as with data on magnetic tape that has been obtained from live neuronal experiments. Figure 2 illustrates the results obtained with a pseudo-random noise source as the input and with the device operated in the autocorrelation mode. Only 12 of the allowable 48 readout channels are displayed in the composite output, or bar graph. The pulse train produced by the STD was essentially Poisson-distributed. Figure 3 illustrates the results of processing data obtained from the auditory system of a cat.†

The incremental values of the delays ($\Delta\tau$'s) used during this processing were 1 msec. The bar graph represents 48 correlation delay values ranging from 2 to 3 msec for the first time-delay interval to an interval of 49 to 50 msec represented by the last horizontal bar. The largest count, ≈ 300, occurred in the twelfth time interval. This interval represented pulse correlations separated by 13 to 14 msec.

The number of times a particular time interval between consecutive pulses occurs in a pulse train, versus the time interval, is also available within the correlator in the form of a time-interval histogram.[1] This differs from the correlation mode inasmuch as the latter measures the time-interval relationship between pulses, independent of whether other pulses are in between; whereas, a time-interval histogram is concerned only with the adjacent pulses. The time-interval histogram contains 1024 discrete reference intervals. Each reference interval is from $(N-1)\ \Delta\tau$ to $N\Delta\tau$ msec long, where N ranges from 1 to 1024, and $\Delta\tau$ may be selected as either 5 or 10 msec. Using the latter, the reference time intervals would be 0 to 10 msec, 10 to 20 msec, etc., until the last, which would be from 10.23 to 10.24 sec. The intervals between pulses are logically compared to reference intervals in coincidence gates which produce a pulse when coincidence occurs. The 1024 histogram outputs may be monitored simultaneously in groups of 8 or 16 by the various forms of readout available.

Since the correlator was built with considerable versatility of connections through switches and patch panels, analytic functions other than those previously mentioned may be used. For example, forms of expectation densities and conditional probabilities may be used by appropriate connections of the coincidence gates, delay circuits, and STD's.

† Supplied by Dr. P. Nelson, Spinal Cord Section, Department of Neurophysiology, NINDB, National Institutes of Health, Bethesda, Maryland.

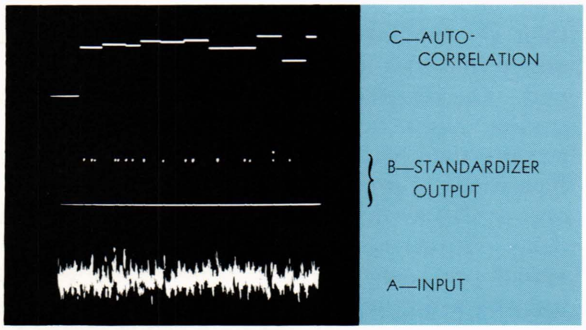

Fig. 2—Composite readout. (A) depicts a portion of the pseudo-random noise fed to the standardizer. (B) depicts standardizer output for the same time epoch. (C) illustrates composite output for twelve time delay intervals, with the correlator in the autocorrelation mode.

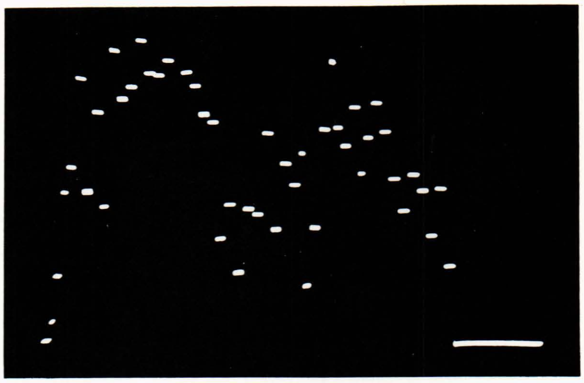

Fig. 3—Composite readout representing an autocorrelation of neuronal discharges from the auditory system of a cat.