A COMPUTER-ORIENTED SYSTEM FOR HIGH-SPEED RECORDING OF OPERANT BEHAVIOR¹

HERBERT BARRY III, WILLIAM J. KINNARD, JR., NATHAN WATZMAN,
AND JOSEPH P. BUCKLEY

UNIVERSITY OF PITTSBURGH SCHOOL OF PHARMACY

A method is described by which large quantities of data, generated at high and variable rates from a large number of test boxes, are recorded on a single eight-channel punched paper tape. The data, which include a record of the occurrence time of each event in $\frac{1}{10}$ -sec units, are in a compact form, suitable for conversion to standard Hollerith punched card codes and for decoding and summarizing by a large digital computer. Experience with the system has demonstrated a high degree of accuracy and reliability, and low operating cost.

Technological advances have often led the way to new scientific discoveries. Conant (1947) pointed out the great stimulation to research and discovery provided by the invention of the battery and the X-ray machine. The mutual cumulative progress of science and technology was expressed by Sarton (1962, page 151): "Much of our experimental knowledge . . . developed almost naturally together with the instruments which human hands had built and used . . . the younger scientists improve the instruments bequeathed to them, and better instruments make better scientists."

The recent development of electronic computers enables unprecedentedly rapid and precise analysis of data. McCann (1965) describes the use of an elaborate system of computers to analyze neural responses. Diverse applications of computer technology have been described by a number of other experimenters, in a monograph edited by Tolles (1964) and in a book edited by Stacy and Waxman (1965). Most of these systems, like McCann's, are designed for precise measurement of action potentials, EEG records, or other rapidly fluctuating input signals. The tremendous capabilities of computers are thereby impressively

utilized, but such systems are very expensive to acquire and operate.

The usual operant-conditioning data consist of on-or-off signals (lever presses, or operation of a reinforcer, such as a feeder or shocker), with a maximum rate of several times per second. The relative simplicity and low rate of the signals permit the use of a computer-oriented system to record and analyze data at a moderate cost. Coded punch patterns on paper tape, suitable for computer input, can be generated rapidly, cheaply, and accurately by standard electric signals. It is feasible to record on a single paper tape the data obtained concurrently from several sources. Ellen and Wilson (1964) described a system for recording on a single paper tape the lever presses and deliveries of reinforcement occurring in five test boxes. The punch was activated at regular intervals, 5 per sec; whenever an event occurred in one of the test chambers, its corresponding position on the tape was punched, along with a code to show whether it was accompanied by a reinforcement. This technique thereby provided a record of the time of each successive event, in $\frac{1}{5}$ -sec units, without requiring a separate code for time units. The alternative method of using event-marker pens on a polygraph record, moving at a sufficiently fast speed to permit measurement of time intervals in $\frac{1}{5}$ -sec units, would produce extremely bulky data, requiring manual analysis which would be time-consuming, tedious, and almost certain to introduce tabulating errors.

The paper tape records obtained by Ellen and Wilson (1964) have serious drawbacks as

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computer input and apparently were not used for this purpose. The punching rate of 5 per sec generates the same amount of tape (150 ft per hour) regardless of variations in activity of the animals; expensive computer time would be consumed by reading the empty time signals which constitute the majority of this record. Their punch codes are not compatible with the Hollerith code (IBM Manual, 1960), the most commonly used code for input to computers. Their use of a separate punch position to record each of the five test boxes is inefficient; Herrick and Denelsbeck (1963) were able to record eight different magnitudes of lever deflection on four paper tape punch positions by means of a binary code of numbers.

The present paper describes a system for recording three different types of event in each of eight test boxes, and the time of each event in $\frac{1}{10}$ -sec units, by means of coded punch patterns on a single paper tape. The record is compatible with the Hollerith code and is compact, with different numbers of events producing corresponding differences in the length of the tape. The use of a large, digital computer for decoding and summarizing the punched codes is also described.

Event and Time Records

Albino rats are tested in a Sidman avoidance schedule which requires separate avoidance and escape responses. Shock is programmed to be turned on for a duration of 2 sec, with a 5-sec S-S interval between shocks. Depression of the escape lever turns off the shock, initiating the 5-sec S-S interval. Presses on the separate avoidance lever postpone onset of the next shock by 20 sec (R-S interval) provided the shock is currently off; this lever is ineffective while the shock is on. Heise and Boff (1962) reported on the use of the same schedule, with longer time intervals (5-sec shock durations, 10 sec S-S, 40 sec R-S).

This schedule is used concurrently in eight separate test boxes. The paper tape recording system is programmed to punch 24 different event codes, representing three events (press on the avoidance and escape lever, and shock onset) in each of the eight boxes. Each time any of these 24 events is punched, its event code is immediately followed by a punched time code, in $\frac{1}{10}$ -sec units. The time code is provided by a clock which cycles through 40

successive time units. At the beginning of every new cycle of 40 time codes (4 sec), a special zero time event code is punched. The code for the $\frac{1}{10}$ -sec time unit associated with each event provides a sufficiently detailed record to differentiate among small fractions of a second, desirable for calculating shock escape latencies and interresponse times of bursts of lever presses in quick succession. The zero time event code, every 40 time units (4 sec), provides an accurate time marker when several seconds elapse between events, as in the case of slow lever-pressing rates or successive shocks in the absence of responses.

Paper Tape Codes

The codes for the 24 events and 40 time intervals are shown in Fig. 1. They are based on the binary-coded-decimal (BCD) numerical system. A single punch in positions 1, 2, 4, and 8, labeled at the left of the tapes, corresponds to the numbers 1, 2, 4, and 8. Numbers 3, 5, 6, 7, and 9 are coded by an additive combination of two or three punches; for example, the code for 7 consists of punches in the 1, 2, and 4 positions. This BCD code is used to identify the number of the test box and the units digit of the time codes. The three types of event, and the tens digit of the time codes, are coded by punches in the 0 and X positions (zone punches). The Hollerith codes, shown above the tapes, indicate that each combination of numerical and zone punches corresponds to a letter of the alphabet or other conventional symbol. Thus, each of these paper tape codes has an equivalent code on standard IBM punch cards.

The special event at the beginning of each cycle of 40 time steps is shown as the zero time event (4, 8, X positions), followed by the time code (C position) for the zero time. An efficient and economical record is provided by the use of most of the codes as both events and times; the two functions for the same code are distinguished from each other by their sequential positions following the zero time event, with regular alternation between the event and time codes. If for any reason the correct sequence were lost, it would be regained within 4 sec by the occurrence of the next zero time event.

The event and time codes are filled in black in Fig. 1, to distinguish them from the small sprocket holes and from the parity check,

Fig. 1. Paper tape punch codes for events and times.

labeled C. The parity check is punched whenever an even number of other punch positions are activated; consequently, every correct code has an odd number of punched positions. This provides an error-checking method, because a mechanical failure or incorrect activation of one of the punch elements results in an even number of punched positions.

Punch Programming Mechanism

Figure 2 shows a block diagram of the programming logic. The input for the events consist of 24 event storage devices, one for each of the three types of event in the eight test boxes. The occurrence of an event activates (sets) its corresponding event storage, which remains set until reset by a separate signal.

The mechanism for selecting the events to be punched is shown in the event programming section of the block diagram. The test box scanner, driven by the scan clock at the rate of 1000 pulses per sec, cycles through eight positions, each of which corresponds to one of the test boxes and its coded punch positions. When the scanner reaches a test box in which one of the three event storage devices has been set, the scanner activates the cor-

responding alarm and scan device for the shock, escape, or avoidance event. This in turn activates the event programming units which hold the scanner at the same box, provide the punch positions for the type of event (0X, X, or 0), and lead to the punch activation. As soon as an event is punched, its corresponding event storage is reset. This removes the signal from the inhibit module and allows the test box scanner to resume searching the test boxes in sequence. In the very rare instances when two or all three event storage devices for the same test box are activated simultaneously, the shock is punched first and the avoidance is punched last, corresponding to the likeliest sequence of events occurring in close succession.

The punch activation system includes the punch timing units which regulate the punch duration (4.5 msec) and the minimum interval between successive punches (12.2 msec), providing a maximum rate of 60 punches per sec. The punch timing first activates the gating event unit, to punch the codes which are portrayed on the left-hand side of the event and time format encoder. This is followed by activation of the gating time unit, to punch the codes from the time interval register gates, as

Fig. 2. Block diagram of the programming logic for the paper tape punch recording system.

portrayed on the right-hand side of the event and time format encoder. There is available a push-button to generate manual leader, consisting of a series of punches in the C position, which is useful for marking the beginning or end of a test session.

For the time interval programming, the time interval clock delivers one pulse every 100 msec ($\frac{1}{10}$ sec). This operates the time interval register, which consists of six units corresponding to six punch positions, turned on or off in a binary counting sequence to form the 40 successive time codes. The beginning of the sequence activates the special zero time event code. A time code is punched only after the punching of an event code. During the 4.5 msec that the time code is being punched, the time interval control is inhibited to prevent a change from occurring in the input to the event and time format encoder while the punch is being activated. This delays by a maximum of 4.5 msec the time that a new

pulse from the time interval clock reaches the time interval register, but it does not alter the regular 100-msec cycle of pulses from the time interval clock. Thus, an accurate "real time" is provided throughout the session.

The event storage modules cannot register the occurrence of a new event until the prior event stored in the same module has been punched. The minimum interval of $\frac{1}{30}$ sec between successive punched events, with their associated time codes, is approximately the same as the minimum interval between input signals for successive presses on the same lever, determined by the durations of the lever-press signals. Therefore, successive repetitions of a single event are not likely to be lost from the paper tape record. If several event storage modules are activated simultaneously, a longer time is required for them to be punched, but the maximum punching rate of three events in each $\frac{1}{10}$ -sec time unit provides a large margin above the usual rate of data input. On

the rare occasions when several events occur in the same unit, some may be recorded as occurring in the following time unit, and there may be an occasional failure to record the second of two rapid presses on the same lever. However, these inaccuracies in the paper tape record are minor and infrequent.

Method of Data Analysis

The punched paper tape codes are converted into equivalent Hollerith codes on standard punched cards with the use of an IBM 047 tape-to-card converter. Each card contains 77 codes (punched on columns 2-78). The zero time (C position) has no Hollerith equivalent. By wiring a connection on the IBM 047 plug-board, this is punched on the cards with one of the unused Hollerith characters (a period).

An essential part of the system is the use of the IBM 7090 computer to analyze the voluminous data. Figure 3 shows a flow diagram of the program, written in FORTRAN, for decoding and summarizing the data. The computer first reads several cards which contain parametric specifications, such as the length of time to be included in the data analysis. These provide flexibility to the program, determining many of the "Yes" or "No" branches from the decision points shown in diamond-shaped boxes. The computer then reads the data, one card at a time, and processes, for each card, the 77 data bits (event and time codes) one by one. The flow diagram shows the recycling loops by which the computer reads each successive data bit or card.

The program includes a thorough check for

Fig. 3. Flow chart of the FORTRAN program for the IBM 7090 computer to decode and summarize the data.

errors in the data. After each zero time event, the successive data bits should alternate between event and time codes. If an event is specified, only 24 of the 40 codes are valid; if a time is specified, successive codes must be in the proper sequence. In each test box, the shock onset should be 20 sec after an avoidance, or 5 sec after a shock escape, or 7 sec after onset of a shock which was not escaped.

The duration of the time segment, which is the unit of analysis for the summary tables, is specified in one of the initial parameter cards. When the specified time is completed, the program postpones terminating the time segment as long as the shock is on in any of the test boxes, in order to ensure that each escape is placed in the same time segment as the shock which it turned off. Six summary tables, each presenting the data from all eight boxes, are generated for each time segment. The first of these summary tables shows the number of occurrences of the events, classified according to their relationships with other events. For example, the presses on the avoidance lever are divided into five categories: (a) avoidances which followed a prior effective avoidance, (b) the first avoidance following a shock escape, (c) the first avoidance following a shock which was not escaped, (d) an avoidance lever press during the shock (and thus ineffective), and (e) an avoidance occurring more than 10% later than the time shock should have occurred according to the schedule; this 10% tolerance provides a large margin beyond the normal variation in the recorded times. The other five summary tables give the following frequency distributions of temporal relationships: (a) interresponse times between successive effective avoidances, (b) latency of the first avoidance following escape, (c) latency of the first avoidance following non-escaped shock, (d) latency of escape following shock onset, and (e) interresponse times between successive redundant presses on the escape lever. For each of these frequency distributions, the mean and standard deviation are calculated. These summary tables are printed on standard sheets and also punched on cards.

Sources, Costs, and Reliability

The transistorized programming modules for the paper tape recording system, which perform the functions shown in Fig. 2, are available in the form of slide-in cards from

the Massey Dickinson Co., Saxonville, Massachusetts, for \$4000. The punch is Model 420P, manufactured by the Tally Register Corp., Seattle, Washington; the Massey Dickinson Co. provides it for \$1415, rack-mounted and adapted for inputs from the programming modules. Similar transistorized programming modules for the continuous avoidance schedule in eight test boxes, providing the input signals to the 24 event storage units, cost \$5500 from the Massey Dickinson Co. These prices include all necessary accessories, such as 24 v dc power supply, wires, and mounting racks.

Initial cost of the system includes the time and skilled labor required to connect programming and recording modules and to program the computer to decode and summarize the data. These costs cannot be predicted precisely, but the purchaser must be prepared to wait several months, and to spend several thousand dollars for electronic and programming services and for computer time, before the system is fully functional. Many hours must be spent by an experienced electronics technician, making several hundred wiring connections on several dozen programming modules. Help can generally be obtained from the company or companies supplying the equipment, but if the experimenter expects to receive a complete, fully operational system, this should be made explicit in the purchase agreement. Likewise, many hours of work by an experienced programmer are required to prepare instructions for the computer and to accomplish the series of "debugging" and test runs needed to achieve the necessary correctness of all the programming instructions. Computer centers will generally provide help in the use of the facilities, and also the services of a programmer, if needed. The source program which performs the function shown in Fig. 3, written in the FORTRAN language for the IBM 7090 computer, consists of more than 1000 separate instructions.

Once the capital investment has been made, and the system is functioning, maintenance and operation costs are modest. The transistorized modules require no maintenance and very infrequent repair or replacement. The paper tape punch needs routine oiling, every few weeks or months. A huge quantity of detailed and accurate data can be obtained; a typical 2-hr test session contains approximately 25,000 bits of data (1500 events, with their time codes,

in each of eight test boxes). The quantity of paper tape (250 ft) and punched cards (350) on which these are recorded cost less than 50 cents.

The IBM 047 machine requires less than 30 min to convert this quantity of tape into cards. Its maximum rental cost is less than \$1.00 per hour, based on 40 hr usage per week; it is similar to the IBM 026 key punch, with the added capability of tape-to-card conversion, and is obtainable at $2\frac{1}{2}$ times the rental of the key punch. For the IBM 7090, \$5.00 per min seems to be a typical usage rate at computer centers. The program which decodes and summarizes the data for a 2-hr session in four half-hour time segments requires approximately $1\frac{1}{2}$ min of computer time, with magnetic tape input and output. The conversion from 350 input cards to tape, and from output tape to 30 printed sheets and 192 cards, requires approximately 1 min. This input-output function is generally available "off-line" without extra charge on a small, satellite computer, such as the IBM 1401. The option in the program for the complete print-out, showing each of the 12,000 events in sequence with its cumulative number and time, is seldom chosen; it requires 5 min of computer time and produces more than 200 pages of printed output.

Errors in the punched paper tape, detected by the parity check on the IBM 047 and by the error checks in the computer program, are very infrequent; in most data samples of 25,000 punch codes there are fewer than 25 errors (.001 frequency). Some data samples are error-free. In most cases the errors can readily be corrected, either on the data cards generated by the IBM 047 machine or on the computer output. The punch will probably malfunction occasionally due to a failure in a programming module or in the punching mechanism. Such malfunctions are sometimes not detectable until the conversion to cards by the IBM 047 or until the IBM 7090 output is seen; it is thus desirable to proceed to these steps as soon as possible after the tape is generated. The paper tape recording system fails relatively seldom in relation to its speed and volume of operations.

Alternative Equipment and Techniques

In place of the transistorized modules performing the functions shown in Fig. 2, electro-

mechanical timers, steppers, and relays could be substituted. The scan clock would have to operate at a much slower rate than 1000 pulses per sec; resulting inaccuracies in the data would be infrequent and minor. For programming the continuous avoidance schedule in the eight test boxes, it would likewise be feasible to use electromechanical components to activate the 24 event storage modules, with the use of suitable output drivers to connect electromechanical output pulses with the input for transistorized event storage modules. However, the higher operating speed and greater reliability of transistorized components make them definitely preferable, and they do not cost much more than the equivalent high-quality electromechanical devices.

As an alternative to the Model 420P Tally punch, with a maximum rate of 60 punches per sec, other models are available, at somewhat higher prices, with maximum rates of 120 and 150 punches per sec. A number of companies manufacture transistorized modules and paper tape punches which can accomplish the same functions as the system described. However, the user of equipment from other sources should make sure that the specifications are suitable with respect to voltage, duration, and other characteristics of the electronic signals, especially if the programming modules are obtained from one source and the paper tape punch from another.

The system described requires conversion of the data from paper tape to cards, and then from cards to magnetic tape, for processing by the large computer. Methods of eliminating one or both of these conversions should be considered. The data can be punched directly on cards with a modified IBM key punch (Polidora and Main, 1963), but it is not likely to be suitable for recording continuous operant responses, because of its slow maximum rate (18 columns per sec) and the $\frac{1}{4}$ -sec delay when starting each new 80-column card. The IBM 1401 or other small computer, instead of generating the magnetic tape for input to a large computer, could be programmed to provide abbreviated summaries and calculations of the data. Magnetic tape can be generated directly from paper tape, but the necessary tape-to-tape equipment is less commonly available than the card-to-tape equipment. If tape-to-tape conversion is used, additional error checks and compensations in the computer

program may be needed to replace the identification of errors by the parity check in the tape-to-card conversion and the correction of these errors by changing one or more of the cards.

It has recently become feasible to record data signals directly on the very high-speed and compact magnetic tape generally used as the input for large computers. Such magnetic tape recorders, although more expensive than paper tape recorders, are likely to become increasingly widely used. In addition to their advantages of higher speed, greater compactness, and direct computer input, magnetic tapes permit much longer uninterrupted records than the maximum of 120,000 data bits on a 1000-ft roll of paper tape.

The IBM 7090 is the most commonly available of the large computers. However, the FORTRAN program can be adapted for any of a wide variety of digital computers which accept FORTRAN instructions. Equivalent programs can be written in any of the other standard programming languages. The use of larger and faster computers, such as the IBM 7094 and some in the new IBM 360 series, would be expected to reduce computation costs by decreasing computer time more than they increase the charge per unit of time. This is indicated by experience with conversion of the FORTRAN program portrayed in Fig. 3, originally written for use on the smaller and slower IBM 7070. The higher cost of 7090 computer time was more than compensated for by the fact that the equivalent program required less than one-fifth as much computer time on the 7090 as on the 7070.

The present program was designed to obtain data analyses which might be expected to provide measures for differentiating the behavioral effects of different drugs, and different dosages of the same drug, from each other and from the placebo condition. The different categories of responses provide a variety of measures that can be compared with each other; the frequency distributions of temporal relationships show patterns of behavior, differentiated among very small temporal units ($1/10$ sec). Other programs could be written for different purposes. In particular, it would be possible further to analyze sequential relationships, such as the avoidance interresponse times as a function of the serial position after the last prior shock (Wertheim, 1965) and autocorrela-

tions for successive interresponse times (Weiss and Laties, 1965).

Programming by the Computer

In addition to their function in analyzing data, computers may be programmed to generate and control experimental events, including those determined by the subject's responses. The speed and precision of the computer provide great assets for such a function. The article by Weiss and Laties (1965) reports such a feedback system; several of the articles in the volumes edited by Tolles (1964) and by Stacy and Waxman (1965) likewise describe the use of computers for programming experimental events.

Applied to the present system, such programming would be advantageous, not only by replacing the timers and other programming modules, but also by generating time intervals in the same precise, uniform time units used to record and analyze data. Unfortunately, it is very expensive to use a computer for several hours per day to control experimental events, even in the case of relatively small computers, such as the LINC. Such computers can provide immediate verifications and summaries of the data, but the complete analyses, such as those portrayed in Fig. 3, generally require a computer with the capacity to store and analyze larger quantities of data.

New computers designed for continuous programming, recording, and analysis of laboratory data, such as the IBM 1800, are likely to be more economical and have greater capacities for data analysis than the computers hitherto used in laboratories. Other technological advances may be foreseen. The simultaneous sharing of a single large computer by several different users, connected to the computer by remote consoles, has already been applied to the recording and analysis of data; simultaneous programming might also be feasible, with the cost being divided among many experimental stations. However, any present and prospective system for "on-line" programming and recording as well as data analysis by a computer is likely to be much more expensive than the system described for computer analysis of data programmed and recorded "off-line" from the computer.

CONCLUSIONS

Most experimenters who wish to use a high-speed recording system would probably prefer to include modifications more suitable for their purpose, rather than copy the exact system and components described here. Some modifications require only minimal changes in logic and components; an example would be to reassign the 24 event codes by recording more types of events in fewer test boxes, or fewer types of events in a larger number of boxes. Changes in components or techniques of data recording, such as alternatives to the paper tape recording or tape-to-card conversion, would require more extensive modifications. Any substantial change in the computer program would also be a major undertaking.

The many, varied uses of computers in behavioral research indicate early fulfillment of the prediction by Wrigley (1957), "that electronic computers are going to play much the same role for the statistically minded psychologist as the telescope has for the astronomer and the microscope for the biologist: the role of an instrument leading to greatly widened horizons." The development of computer technology has been extremely rapid; most of the information on computer usage in Wrigley's (1957) article is already outdated. Even more rapid change is to be expected. Some potential users of computer-oriented data recording systems feel inclined to wait until the techniques are more stabilized. But it would be pessimistic to expect technological development to become much slower at any time in the foreseeable future. Even though the new techniques of today will probably be commonplace or superseded within a few years, behavioral scientists have the duty and privilege of participating in, and thus contributing to, the current advances in technology.

The present paper is intended to contribute to this technological development by helping other experimenters to establish computer-oriented data recording systems. Even if such systems differ from the present one in many

respects, the ideas and experiences presented here are expected to point out some of the directions to be taken and errors to be avoided. For the user of such systems, it is very desirable to have the benefit of prior experience, whether one's own or communicated from somebody else. In addition to the information presented, duplicates of the punched-card FORTRAN source programs for the IBM 7090 and 7070 computers, and further details on the programming circuitry, will be furnished on request.

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