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On-line Apple II for the recording and analysis of complex motor movements

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The system described here was prompted by the need for a method of separately recording various components of a complex motor act. The task involved vertical, horizontal, and turn components. Our particular interest was the relation between integration of components and level of skill demonstrated. The peripheral equipment provides a separate analogue output for each component and plugs directly into the Apple's game-paddle input. Trial data are stored directly on disk and can be retrieved for subsequent graphical plotting and analysis. The Apple II accommodates up to four inputs and returns results for movements as fast as .05 sec. The programming system can be used, without modification, for a wide variety of motor tasks. No additional interface or clock is required.

For several years, we have been involved in studies investigating fine motor skill acquisition in young children (Hogg & Moss, 1983; Moss & Hogg, 1981, 1983). Our most recent work involves both nonhandicapped and mentally handicapped children and is concerned with the development of the ability to plan and sequence movement components in a complex motor action. In real life, skilled motor activity often demonstrates considerable integration of the essential components. Rather than each being executed in a discrete linear fashion, the components tend to be collapsed together into a smooth, uninterrupted sequence in which they frequently overlap temporally. The development of this ability to sequence and integrate motor movements is a crucial aspect of skill acquisition (Connolly, 1973).

Our interest in integration led to the need for a suitable experimental task with which to measure such processes. It was necessary that the task involve several distinct components, which could be completed simultaneously if the child chose to do so. The interrelationships between such components were likely to be complex, and the movements very fast, implying the need for some form of electronic recording. The system developed to meet these objectives was based on the on-line use of an Apple II microcomputer.

PERIPHERAL EQUIPMENT AND PROCEDURE

The equipment consists of a small square table, on the top of which is a picture of a rabbit's face. A

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triangular-shaped piece of the face, corresponding to the rabbit's nose and mouth, is removable and is attached via a knob to one end of a metal rod protruding through a slot in the tabletop. At the other end of the metal rod, underneath the table and attached to the rod via mechanical linkages, are three variable resistors that act as position transducers. The metal rod is free to move within predetermined limits in the horizontal and vertical directions and to rotate through 90 deg. The one rotary and two slider-type resistors are commonly used in radios and hi-fis and are readily available.

The basic experimental task requires the subject to complete the rabbit's face by inserting the "missing" triangular-shaped piece of the picture. Successful completion of the task causes the rabbit's eyes to flash alternately and a siren tone to be emitted.

The rabbit's face may be located in two positions. In the forward mode (Figure 1), the face is placed flat on the table at the subjects midline. Correct insertion of the missing piece requires the knob, to which the piece is attached, to be pushed down, pushed forward, and turned clockwise, although not necessarily in that order.

In the reverse mode (Figure 2), the rabbit's face is raised above the tabletop and to the left of the subject. Completion of the task requires the subject to reverse the locating procedure described above. Thus, the starting point of one mode is the finishing point of the other. Depending upon the starting position, the subject may be required to complete any or all of the three movement components.

The three variable resistors are linked to the control rod in such a way that it is possible to resolve each movement component independently into a corresponding and linearly related change in electrical resistance. By selection of the appropriate values of resistor (in this case, 150 kohm), it is possible to connect the out-

Figure 1. The forward mode. Completion of the rabbit's face requires a push down, push forward, and clockwise turn.

put from the peripheral equipment directly into the game-paddle input of the Apple II. For each resistor, the fixed contact is connected to +5 V (pin 3 of the game input/output connector). The sliding contact is connected to the appropriate game-controller input for that particular resistor.

The Apple provides for four such inputs, of which our system used three. These correspond to pins 7, 10, and 11 of the connector [Details of the game input/output facilities can be found in the *Apple II Reference Manual* (Apple Computer, Inc., 1981, p. 100).]

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The computer should scan each resistor in turn at high speed, building a moment-to-moment picture of each component's displacement as the piece is located. Each trial is stored on disk for subsequent retrieval and analysis.

Initial Disk-Scan

Storage of trial data is achieved by a machine code routine using the RWTS (Read or Write a Track and Sector) subroutine. This permits individual access to

each of the 560 sectors of 256 bytes each. [Full details of the use of this routine are given in the *Apple II DOS Manual* (Apple Computer, Inc., 1980, pp. 94-98).] Results from each trial are stored in single sectors progressing along the disk from sector 0. If RWTS is used, there is no space required for DOS. Initial running of the program scans the trial storage disk for the first available sector.

Text Insertion

An option at the beginning of each block of trials is to insert up to 256 characters of text into the next available sector. We use this feature to provide information relating to the independent variables, such as session number and subject group. Subsequent analysis routines can scan these sectors to determine automatically the appropriate category of each independent variable.

Calibration

Prior to each session, and, optionally, before each trial, the user defines the required endpoint for the movement. The lever is set to the required point and the program records the resistor values corresponding to this position. The calibration facility is valuable, in that it permits a range of movements to be investigated with a single piece of experimental equipment. Also, the program works with other apparatuses that use the same basic principle. The fact that the movement endpoint is

Figure 2. The reverse mode. In this situation, the knob must be pulled up, pulled back, and turned anticlockwise.

defined prior to a session means that the effects of wear and tear on the mechanical parts are reduced to a minimum.

During initial piloting of the equipment, it was necessary to modify the calibration routine. Setting the calibrated values to the exact endpoint of the movement was a very stringent requirement, and made no allowance for the flexing and slight variations of the mechanical parts. This made termination of the data-recording routine somewhat unreliable. The problem was eliminated by arranging the program to slightly adjust the calibrated values. For a movement in the positive direction (resistor values increasing as the target is approached), the calibrated values were set lower; for the negative direction, they were set higher. An adjustment of 3 units (in a maximum possible displacement of 255) was adequate.

The analysis routines operate independently of the actual displacement shown by each resistor, even if this occurs from one trial to the next. The principle is to determine the maximum and minimum recorded values for each movement component, and to use these to rescale the range from 0 to 1. Subsequent analysis then proceeds on the basis of movement proportions.

Auto Start

Recording from the experimental equipment starts automatically as the movement commences, a facility with obvious advantages. This was achieved by writing a program loop that cycles as long as the paddle values from one scan to the next remain identical. A change in any of the movement components causes recording to commence. In practice, it was necessary to include a small error factor, since paddle recordings tend to vary slightly, even with the control static. Fluctuations of ± 2 units were ignored for these purposes. This error level resulted in reliable nonstarting with the control-lever static, yet produced prompt and accurate starting of the data-recording routine when movement was initiated.

Scanning of Movement Components

The Apple II paddle-reading routine utilizes a "one-shot" timing circuit. In the circuit, the time to trip

depends on the setting of the paddle resistor. With the Y register initially zeroed, the subroutine alternately checks the state of the timer and increments the register. Incrementing ceases when the timer trips, and the paddle value returned is the number in the Y register (0 to 255).

The execution time for this subroutine is not fixed. It is quicker to return a low paddle value than a high one. However, the simple logic of this system makes it relatively easy to incorporate a machine code routine that eliminates the problem. The routine is in the form of an additional loop, the number of cycles executed being inversely related to the returned value. This approach obviates the need for an external clock, since the number of paddle readings is now a linear function of time. In our program, a complete paddle reading and recording is executed in 2.93 msec, and thus each of the three component positions is scanned every 8.79 msec (i.e., approximately 113 times/sec). This is a good level of resolution for all but the fastest ballistic movements.

Linearity of the time scale is essential. The paddle-reading routine resides in the Apple's ROM at location \$FB1E, and requires that the X register contains the reference number of the paddle to be read (0 to 3) before being executed. The instructions appear in Table 1.

The time taken to complete the routine can vary. For example, the number of machine cycles to return a Y value of 0 is 25; for 100, it is 1,125, and for 255, it is 2,835.

The modified routine, residing entirely in RAM and making no reference to the built-in software, appears in Table 2.

The number of machine cycles to complete this routine, for all Y values from 0 to 254, is 2,844. If Y = 255, there is 1 extra cycle. The time scale is thus perfectly linear, except for a .04% error on the highest value.

Data Storage

From onset of movement to completion, the paddle readings are stored consecutively in 62 allocated pages of memory. This permits a maximum movement time of approximately 45 sec. Typical times for our task were between 0.5 and 4 sec for a competent child, and up to

Table 1
Instructions for Paddle-Reading Routine

PREAD	LDA \$C070 LDY #\$00 NOP NOP	START TIMER
PREAD2	LDA \$C064,X BPL RTS2D INY BNE PREAD2 DEY	START OF COUNTING LOOP. TEST STATE OF TIMER IF POSITIVE THEN FINISH
RTS2D	RTS	RESTART COUNTING LOOP. (UNLESS Y = 0) IF Y = 0 THEN Y = 255 END OF SUBROUTINE

Note—For clarity, symbolic names have been replaced by absolute addresses.

Table 2
Modified Paddle-Reading Routine

PREAD	LDA \$C070 LDY #\$00 NOP NOP	START TIMER
PREAD2	LDA \$C064,X BPL FINISH INY BNE PREAD2 DEY NOP NOP STY CHAR RTS	START OF COUNTING LOOP. TEST STATE OF TIMER BRANCH TO AUXILIARY LOOP IF POSITIVE RESTART COUNTING LOOP. (UNLESS Y = 0) IF Y = 0 THEN Y = 266
FINISH LOOP	STY CHAR NOP NOP NOP INY BNE LOOP RTS	STORE RESULT FOR REFERENCE END OF SUBROUTINE STORE RESULT FOR REFERENCE START AUXILIARY LOOP RESTART AUXILIARY LOOP (UNLESS Y = 0) END OF SUBROUTINE

20 sec for the initial trials of some younger children. Attempts lasting longer than 20 sec rarely met with success.

At movement completion, the paddle-reading data are "sampled" to fit in slightly less than one page of store, so that each trial can fit on a single disk sector. Remembering that the components are recorded 123123123, etc., groups of three are sampled according to the number of pages used during the trial (e.g., if six, then every sixth group). If required, data are then written into the next available sector. Trial data occupy bytes 0 to 250. The remaining bytes hold the number of pages from which the data were sampled (to calculate movement times), the direction of movement (forward/reverse), and a code to distinguish trial sectors from text sectors.

It is possible to store each page of sampled trial data in a separate buffer and to dump this onto disk at the end of a session, rather than after each trial. There is enough RAM space to do this, and the availability can be further increased at the expense of reducing the maximum recordable movement time (i.e., by reducing the 62 allocated pages). In the present instance, however, trial-by-trial storage was adopted for reliability. The setup was used in a variety of locations, and some of these were prone to static buildup. The result of this, usually manifested when the child shuffled in the chair or shifted position, was for the computer to initiate a cold start. It appeared to be better to lose one trial than a whole group.

Reinforcement

Data recording is terminated at the first scan on which all components reach their defined values for completion. The slight fluctuations in mechanics and paddle reading make it necessary to include a small

error factor, which is achieved by slightly reducing the required settings from the initial calibration. This ensures a reliable termination of recording at the movement end.

Immediately following completion, the flashing eyes and tone are activated via one of the computer's annunciator outputs. The program then enters a loop in which reinforcement continues as long as all movement components are at their endpoints. This permits the child to continue manipulating the lever and to establish the contingency between the position of the piece and reinforcement. When appropriate, the experimenter terminates this loop from a hand-held button connected to the maskable interrupt line. The program then moves to optional data storage, recalibration, and the next trial. The system is extremely reliable and easy to use, giving rapid transit from one trial to the next. The only maintenance in 5,000 trials has been replacement of the three variable resistors, after approximately 3,000 trials. This was merely a precautionary measure, since no evidence of malfunction had been detected.

Location of Programs

The overall system consists of a main program in uncompiled BASIC, a set of machine language routines, a memory allocation for the paddle-reading data, and a one-page buffer into which the sampled trial data are read prior to disk storage. The locations of these various programs, and the number of bytes allocated for paddle data, may be varied to suit the needs of the user. (An exception to this is the uncompiled BASIC program, since the Apple's interpreter always starts at location 2051. This limitation can be overcome by compiling this part of the program.) For our system, the decimal locations are as follows:

Main program in BASIC 2051-4713
 Paddle data 8192-24319
 Machine language routines and buffer 32232-35609.

This amounts to a total RAM usage of approximately 22K.

DATA PRESENTATION AND ANALYSIS

Since trial data are already stored on disk, it is possible to perform direct computer analyses, avoiding the need to transcribe large quantities of numbers. The sophistication of such analysis is limited only by the capacity of the machine being used. An outline of the operations that we are presently able to perform illustrates the power and convenience of the overall system.

Graphical Plots of Trials

This is a simple but illuminating way of presenting individual trial data and can be plotted on the screen immediately following a trial if required. Figure 3 illustrates four typical patterns of action. Such data plots provide a strong visual impression of the quality of the movement: for instance, the extent of planning and the smoothness of execution. The degree of integration (overlap between components) can also be seen. From printouts such as these, we have discovered that many children have individual movement patterns that are stable over large numbers of trials.

Characterization of Individual Trials

We have been concerned with 21 movement variables used to characterize individual trials. These include movement times for each component and for the overall location, degree of integration (overlap) between components, number and depth of reversals (movements away from the endpoint), and number and length of plateaus (periods when a component has been initiated but remains static for a time). Obviously, each of these aspects has to be precisely defined.

The complete analysis is achieved in two parts. The first program is the most lengthy part of the procedure, deriving the basic parameters from which the levels of each variable may be calculated. The routines are designed to accept total paddle displacements of any value from 0 to 255, so that any starting and finishing positions may be adopted (including having one or more of the components initially at their endpoints). Sensible values are returned for all parameters even if a component is completed in 0.05 sec (giving four data points). The program is in compiled BASIC and uses a dual disk drive. Each trial sector takes about 3 sec to analyze, the results being written onto a duplicate disk at exactly the same sector location. It is these disks of initial analysis that are scanned by the pool-and-display programs.

Analysis of the sectors containing text uses a separate program in conjunction with a data file on the subject's names and the group to which they belong (nonhandi-

Figure 3. Graphical plots of four typical patterns. Solid lines represent vertical, hatched horizontal, and dotted turn components. (1) Trial demonstrating no clear motor plan. Note the frequency reversals of direction. (2) Individual components smoothly executed but totally discrete. (3) Integration of turn and horizontal. (4) Integration of all three components.

capped, Down's syndrome, etc.). The text is scanned for the subject's name and details of the session, and the relevant information from the data file located by matching to this name. Subject information and details of the session are written onto the same sector number on the duplicate disk. As a result, these sectors contain categorical data giving the appropriate level of each independent variable. The exception is that of movement direction (forward/reverse), which is coded on each trial.

Pool and Display System

Our research involved over 4,000 trials on the rabbit apparatus, under a complex series of independent variables. As noted, characterization of the individual trials yielded over 20 dependent measures. In addition to rabbit placement, children also received scores on 19 subject variables, so named because each child obtained one score on each variable. These scores included two further tests of motor performance, one derived from pursuit rotor measures and the other from rod placement tasks. In addition, there were measures on the ADIECAS questionnaire (Evans & Hogg, in press) giving estimates of attention/distraction and excitation/

inhibition, an assessment of mental age (MA), and measures of hand size and area. These were stored on a random access file. Finally, four estimates of each subject's consistency in performing repeated motor actions were included. Two of these were derived from rod placement data; the other two were computed directly from the rabbit placement initial analysis, and were automatically stored in the appropriate cell of the random access subject data file.

The Pool and Display programs were developed to make this a more tractable problem. They provide a series of interlocking machine code programs, compiled from BASIC, which scan the initially analyzed rabbit placement disks plus the subject data file. During scanning, the 21 dependent variable scores are calculated for each trial, a process that is very fast. The programming system permits the rabbit data to be segregated and pooled with respect to specified combinations of the independent variables, and the means to be printed out. Also, the user may plot the segregated and pooled rabbit results against any of the 19 subject variables and calculate the correlations.

To clarify the means by which this is achieved, initially analyzed disks contain the results of characterizing each trial separately. Each group of trials (a session) is headed by a sector containing information on the appropriate level of each independent variable. The subject data file contains all scores on the 19 subject variables.

For segregating the rabbit data, the number of independent variables one can specify is limited by the storage capacity of the machine. Hence, it is necessary to specify these requirements before scanning the disks. With our system, the number of dimensions is limited to three if just the rabbit data are being considered (e.g., subject group $\times$ movement direction $\times$ session number). If the rabbit data are to be plotted against subject variables, then each subject's results must be kept separate, so the dimensions must be restricted to two.

POTENTIAL

The appropriate approach to analysis depends on the particular research being undertaken. However, there is considerable potential for a combined on-line recording and analysis system.

On-line computer recording offers a very precise method for observing complex motor movements. Direct storage of results permits rapid and sophisticated analysis. Our system can scan and compute 21 dependent variables for 4,000 trials (covering eight disks) in

about 15 min. The calibration facility makes the system flexible and insensitive to wear, and the autostart provides straightforward and accurate trial initiation. Using the Apple's built-in ADC obviates the need for a separate interface and clock.

The flexibility and accuracy of the overall system suggests its application in a wide range of experiments and assessments of motor movements. Although the system records up to three components, the Apple II possesses four game-paddle inputs. With suitable programming, it is possible to observe more complex movements. The sophistication of analyses can be increased to any level required, limited only by the availability of RAM. For longer sequences of movement (up to 45 sec), much finer resolution can be obtained if the data are not compressed, although this naturally requires more disk space. Finally, the speed with which analysis can be performed suggests the possibility of providing instant and selective feedback, either during or immediately following the movement. This points to a potential use for this kind of system in the training and assessment of fine motor movements.

The programs were written and compiled on an Apple II Plus, with DOS 3.3 and 48K RAM.

AVAILABILITY

Listings of the program are available on a cost-of-materials basis.

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