Computer control of memory experiments on a large-scale timesharing system

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This paper describes a computer system for running verbal learning and memory experiments using a large-scale timesharing computer. Its application is illustrated by control programs used to set up, execute, and analyze a series of interactive free recall experiments. While limitations of timesharing systems for experimental control surely exist, they can often be removed by simple hardware or software. Further, a large machine can provide significant advantages in cost and software development over dedicated laboratory minicomputers. It is possible to obtain the advantages of both types of systems by introducing local intelligence to provide more precise timing and flexible control of experimental devices, while retaining the power and hardware and software resources of the large machine.

There are a variety of alternatives for experimenters considering automated research. Possible systems include single-user micro- and minicomputers (Murdock, Dufty, & Okada, 1972), multiuser micros and minis (Santa & Streit, 1978; Scholz & Halff, 1974), networks of small computers (Wallace, Johnson, & Johnson, 1978), general departmental computer facilities (Fitzhugh & Glaser, 1975; Polson, 1978; Proudfoot, 1978), and general university-wide installations (Huesmann, 1969; Hunt, 1969; Potts, 1976).

Each of these systems represents a different level of cost and personal involvement in system development. Obviously, initial expenditures are important in this decision, but there are other equally important factors. For example, a microcomputer system that costs \$3,000 and takes 2 man-years to learn and put into use is more expensive than a \$15,000 system that can be installed and operationalized within 1 month. A system that comes complete with a variety of high-level language processors, utilities, and software tools is likely to be cheaper in the long run than a higher priced system with limited software. Indeed, as hardware costs continue to drop, making minis and micros more available, many users are finding that the limited availability of general software (e.g., operating systems, text editors, file systems and utilities, language translators) is a limiting factor in computerized experimentation (Bowles & Hollan, 1978; Polson, 1978; Scholz, 1978).

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This paper describes the stage-wise development of a computer facility for running memory and learning experiments with adult human subjects, based on a top-down approach to developing computer control. This system was originally implemented on a large university-wide timesharing computer. Our strategy has been to try to obtain maximum utility from a fixed level of involvement by using the available hardware and software resources of the large machine wherever possible at any stage; as stated by Kernighan and Plauger (1976), we "let someone else do the hard part." This approach allows us to focus our efforts and somewhat limited financial resources on those components most crucial to automating experimental control.

We discuss the first stage of this development mainly in terms of control programs used to set up, execute, and analyze a series of interactive free recall experiments. The system has been operational for 3 years and has been used to run a variety of memory experiments, including free recall, item recognition, lexical decision, and category verification tasks. Some aspects of its present status and planned future development are touched on briefly.

HARDWARE

Central-Site Computer

Our experimental control system runs on a moderate-size DEC-10 installation, a KI10 36-bit processor with 256K main core, hardware double-precision arithmetic, and a typical complement of disk (2-RP04 and 2-RP06) and tape drives (2-TU70), readers, and printers. A communication link to an IBM 370/158 provides two-way remote job submission as well as protected access to programs and data files between machines. The DEC-10 system supports remote batch, real-time jobs, priority timeslicing, and networking of remote stations. Subject to approval of the York University computer

Figure 1. Stages in developing a timeshared computer by adding local intelligence.

center, small I/O-bound jobs may be locked in core and run at top priority.

The software available through this system includes a wide variety of high-level language processors, a macroassembler, the SOS/RUNOFF text-editing system, and a macro-interpreted command language (MIC) that provides access to all system parameters associated with a given job.

Local Hardware

The components of the initial system are shown schematically in Figure 1a. Our investment at this stage was a Datamedia Elite 1520 CRT display terminal (\$2,200) with a dual (ASCII/APL) character set and programmable cursor control. It is connected to the DEC-10 by both a 300-baud dial-up line and a 1,200-baud hardwired port. Later, a Polytronics universal response timer (\$600) was added for reaction time experiments (Figure 1b). The timer can be connected through the key board of the terminal or interfaced to simple microswitch response boxes or panels (see Potts, 1976).

THE IFR SYSTEM

The IFR system grew from a need to automate contingent presentation in free recall, in which the stimulus presentation on Trial N+1 depends on some

characteristic of the subject's response on Trial N. The system consists of modular software designed to completely automate the running of a free recall experiment. That is, the system as a whole provides facilities for setting up an experiment, running subjects, and analyzing data. The components of the system (programs and files) are shown schematically in Figure 2.

Word Pools and Stimulus Selection

In memory experiments, subjects are presented a set of stimulus items selected from some larger pool. The stimulus items are usually words, but in general, they consist of any string of ASCII characters, including control characters. This allows a character-oriented interface (Fitzhugh & Glaser, 1975), in which new stimulus presentation devices can be added or changed easily without affecting the overall design of the system.

A "word pool" consists of a series of stimulus items, as defined above. Associated with each stimulus item there may be scale values for that item on one or more variables (e.g., word frequency, concreteness, imagery) used in selecting items for a given subject. The IFR system selects items randomly within a range on these variables (specified for each condition), so that every subject receives a unique list. A word pool is stored as a direct-access file with a record for each item, containing the character representation of the item and its measured scale values. At present, word pools include, among others, the Battig and Montague (1969) norms of categorized words and the Paivio, Yuille, and Madigan (1968) norms.

Taking advantage of the wide choice of languages available on the large machine, we wrote the control programs for the IFR experiments in APL (Iverson,

Figure 2. Design of the IFR system for experimental control. SETUP, CONTROL, and ANALYSIS indicate the operations performed during the corresponding phases of an experiment.

Figure 3. The main blocks of the IFR control program. **BEGIN** initializes experimental parameters (EP) and word selection ranges and then randomly selects a list of NW words. **LOOP** executes NT recall trials with a presentation time of RTIME sec/item and RTIME sec allowed for recall. **WRAPUP** prints and saves the results. The functions called by **BEGIN** and **LOOP** are shown in the Appendix.

1962) and selected FORTRAN for scoring the results and data analyses (Friendly, 1975).

Figure 3 shows the flow of experimental events in IFR and the interaction of software and hardware. In free recall, the subject is given a series of trials in which a list of words is displayed, and then he is required to recall as many of these words as he can. This structure is mirrored in the IFR control programs in **LOOP** over trials that form the core of the programs. **BEGIN** is responsible for initialization procedures and **WRAPUP** saves the subject's data on disk, provides feedback, and sends a complete protocol of the session (presentation details, recall results, and various summary measures) to the high-speed printer.

In the program a clear separation is made between the logic of the experimental events and possible parametric variations. That is, the variable features of the experiment, such as the number of words, number of trials, times for presentation and response, and so on, are read by the **CONTROL** program from the parameter file during initialization (**BEGIN**). The parameter file also identifies the word pool to be used with a specific experiment, and it contains the variables that govern the selection of stimuli from the pool. Thus, no changes to the **CONTROL** program are

required to set up a specific IFR experiment, and the parameter files can be constructed by an interactive **SETUP** program. In this way, the same software can be used by students in laboratory courses to design and run small automated experiments as part of their course work.

Data Management

The large machine is particularly valuable for data management. We maintain a number of large stimulus pools, used across many experiments, and a set of parameter and results files associated with each experiment. As the volume of such data grows, it is crucial to be able to access selected information quickly and easily. One solution to this problem is to develop a comprehensive data-base management system (e.g., Durrett, 1976) for experimental control and data analysis.

However, on the DEC-10, we have again found it possible to take advantage of existing resources. At one level, the operating system provides hierarchical file directories, which simplifies managing many files. At a lower level, the file I/O facilities of the DEC-10 APLSF implementation go a long way toward meeting our needs.

For stimulus pools and parameter files, the use of direct-access files makes stimulus selection quite easy. For example, in APL the instruction,

D ← [C] INFILE

reads component C (a variable-length record) from file INFILE and assigns its contents to a variable D.

The results files present a somewhat different problem, since a subject's data record may contain a heterogeneous collection of data items of varying length, type (character, integer, logical, real), and shape (scalars, vectors, and arrays), and these may vary considerably from one experiment to the next. Our results files are written in binary access mode in a self-describing format. For example, the instruction,

A ⊞ OUTFILE

writes the data item A to file OUTFILE with a header of a few words that encodes the data type, length, and rank (0 = scalar, 1 = vector, 2 = matrix, etc.). Since this information is contained in the file itself, most of the "hard part" of data management is done for us. Programs that access these files need to know the number of components in a subject's data record, but not the details of their composition.

The only drawback of this scheme is that the data files cannot be read directly by standard packaged programs. Still, it is relatively easy to write a small utility program to preprocess the results files for standard analysis packages. The results from most

experiments need to be preprocessed anyway, to cull bad data records, perform preliminary transformations, or calculate various derived measures from the raw results, so this has not been any burden.

EVALUATION

Virtual Apparatus

In interfacing stimulus and response devices, there is often a tradeoff between hardware and software, so that many component operations in an experiment can be carried out under software control from the central machine or by acquiring a special-purpose device.

To make the timesharing computer more versatile, the subject I/O station is regarded as a "virtual apparatus." The physical device at the subject station (a CRT with cursor addressing, for example) has a certain range of basic sensorimotor I/O capabilities. A virtual apparatus, like its physical counterpart, is composed of components, but many are fashioned in software rather than hardware. Within limits, we can design, build, and test a virtual apparatus far more easily and cheaply than we can construct a physical one (see also, Vesonder, Lesgold, & Wolf, 1978). Once it works, we can then evaluate its limitations and make it work better or faster by introducing specialized hardware.

Timing

For example, the difficulty in timing stimulus and response events with sufficient precision is probably most often cited as an inherent limitation of large-scale timesharing systems for computerized research due to the probability of being swapped out of core at any instant.

However, timing is always a matter of degree, in relation to demands of particular tasks. We need to obtain response times to millisecond accuracy and insure that stimulus display times are precise to within 3%-5%. (Typical durations range from 400 msec to 10 or 20 sec per item.)

We have found a solution to the timing problem that more than adequately meets our needs, although it might not prove satisfactory for very brief stimulus durations. The Polytronics response timer handles all the response timing transmitting a one-character response followed by a four-digit time value, encoded as an ASCII string. This timer is relatively inexpensive (\$600), but in our present system, one must be provided for each subject station.

We were able to obtain high-priority privileges, so we decided to solve the problem of presentation duration in software. Small FORTRAN and MACRO programs were developed to be locked in core and executed at high priority to display stimulus information. On-times and delays are provided by writing idle characters, and at 1,200 baud, these times can be resolved to within 8 msec.

Cost

While the top-down approach to development reduces costs on hardware purchasing, there are concealed costs for developing software and using university equipment. The software has to be developed regardless of the approach to automation. However, the cost of the timesharing per connect hour can seem high. In our particular location, these costs have worked out at approximately \$8/h (CPU time plus connect time) during the last 3 years. In the early stages of developing a computer facility, much of the time the equipment is not used to capacity. If the user owns the hardware, then he must pay maintenance on it regardless of whether it is fully operational. However, if someone else owns the expensive hardware, then the user only pays when he is connected and using the system.

Programming Languages

We chose APL as the language to develop experimental control programs because of its extensive capabilities for manipulating character strings and data arrays. Although it is an interpretive language, and therefore somewhat inefficient at execution time, it is highly efficient in terms of programming time.

For comparison with other languages developed for computer control (McLean, 1969; Pinkus & Gregg, 1973; Schölz, 1973), Figure 4 shows the basic Sternberg (1966) item recognition paradigm, programmed in APL. The program chooses digits at random for presentation and presents varied sets within a range of set sizes (one to five), with a .5 probability of a positive probe. Our item recognition programs are much lengthier, since they include options for stimulus type, and parametric values such as intertrial interval. They also include functions for data storage and hard-copy output, including on-line analysis of subject performance indices.

To demonstrate the more sophisticated capabilities of APL, Figure 5 shows the IFR spelling algorithm that checks subjects' responses during recall trials for misspellings and typographical errors. The program calculates a correlational value between a typed response word and each word in the experimental list, based on letter matches and positional proximity. In a recent assessment, a sample of 1,837 responses from several

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      * STERNBERG ANTETI:ASSI:R:K:PROBE:KEY:RESP
111  T←0
112  NEXT:←CLEAR
113  +OUT IF ANTETI←T+1
114  T←0:ASSI←75:R←0:0
115  N←ASSI:K←ASSI:RPERM1:9
116  3 2 DISPLAY BUI+(C*%), (DELAY 1,2)+CLEAR)
117  ENDSET:KEY←72
118  +POS IF KEY=1
119  NEXT:←TEST:PROBE←K+N
110  POS:←TEST:PROBE←K+N:ASSI
111  T←1: 3 2 DISPLAY PROBE
112  R←RESP←0
113  CLEAR
114  +CORRECT IF KEY=RESP
115  WRONG:←NEXT:0 +NOPE ", DELAY 2
116  CORRECT:←NEXT:0 +RIGHT ", DELAY 2
117  OUT:0 +CLEAR
118  T←1 +THANKYOU FOR PARTICIPATING

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Figure 4. Sternberg item recognition program.

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▼ ITM*STR MATCH LIST;R;L
E1] R*STR SIMLIST LIST
E2] ITM←1↑R
E3] ITM←ITM*(REITM≥0.7)
▼
▼ R*WD SIMLIST LIST;I;IT
E1] R←OP1+0
E2] NEXT:IT←(↑IT)↑IT←LISTE1+1;I
E3] →L2 IF 0.75<(↑WD=IT)÷(PWD)↑IT
E4] →L1,R←R,0
E5] L2:R←R,WD SIMWORD IT
E6] L1:→NEXT IF I<↑PLIST
▼
▼ R←A SIMWORD B;RA;RB;M;N;SS;D;X;Y
E1] WORD SIMILARITY ALGORITHM
E2] RA←PA;RB←PB
E3] →0 IF 0=R÷A÷B
E4] SS←(↑N÷(M+A÷B)×1000-1(↑RA)÷B-1RB)
E5] M←N÷(RB,RA)P(RA×RB)PSS+0=SS
E6] XY←(1+RA,RB)Tω1=(,0,1JM+0)
E7] S←(↑X/XY)÷(X/↑(XY+XY-(N(↑PXY)P↑XY)÷1↑PXY)*2)+0.5
E8] R←S×(R÷RA/RB)+0.5
▼

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Figure 5. Spelling correction algorithm used for typed recall. SIMWORD computes a correlation-like statistic for the similarity of two words, A and B. SIMLIST uses SIMWORD to find the similarity between a response, WD, and a word list, LIST. The similarity calculation is only made for list words that have at least 75% letters in common with WD. MATCH accepts WD as correct if the maximum correlation is at least .7.

experiments contained 161 misspellings, of which 1 was misclassified by the algorithm. An equivalent program in FORTRAN (or similar language) would be over 90 lines of code, and the computations would severely strain many small systems.

At the same time, there are some experiments that are inefficient in APL, so we developed a set of low-level routines in MACRO and FORTRAN similar to those described by Proudfoot (1978). In the DEC-10 APLSF implementation, these can be called from APL, so the block functions need not be rewritten.

Future Development

The IFR system and other systems that evolved from it represent the first stage in developing a computerized laboratory in a step-by-step process. The next step is to introduce a small microcomputer as a front end to the large timesharing machine (Figure 1c). The local machine initially handles the timing and control of the stimulus and response devices and leaves the bulk of the work to the central machine. For example, the main frame can send a block of data to the micro that contains all stimulus presentation information sufficient for one trial. The micro would be responsible for interpreting the control information and for handling all device translation and timing. As the micro is integrated into the system, it can provide a basic timesharing system, serving several peripheral subject stations simultaneously. As this stage draws near completion, the programs are developed on the central computer, but run on the local machine. All of the lower level software developed in the early part of Stage 2 are dedicated to improving process control operations. At the end of Stage 2, one would have a mode of operations similar to a much larger departmental computer-controlled facility, at a small fraction of the cost.

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Appendix IFR Functions

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▼ BEGIN
[11] SETCONST
[21] COND+GETSUBJ
[31] RANGE+GETWORDFARM(COND)
[41] EP+GETEXPTFARM(COND)
[51] SEED+SETRANDOM
[61] WORDS+RANGE PICKWORDS NW+EP[11]

▼ SETCONST
[11] EXPT+ 'DEMO- [FR'
[21] BAUD+1200
[31] CFS+BAUD-10
[41] CLEAR+DAVE[25/2+ 27 12]
[51] IDLE+DAVE[27/2]

▼ COND+GETSUBJ
[11] SUBJID+PROMPT 'ENTER SUBJECT NUMBER'
[21] COND+PROMPT 'CONDITION:'

▼ WF+GETWORDFARM COND
[11] FILE+ASSIGN 'PARAM.',3+EXPT
[21] WF+BFILF
[31] RANGE+BFILF
[41] RANGE+RANGE[COND+1]

▼ EP+GETEXPTFARM COND
[11] EP+BFILF
[21] EP+EP[COND+1]

▼ S+SETRANDOM
[11] S+URL+11/11DAYTIME

▼ WORDS+RANGE PICKWORDS NW+ITEM+RAND+V+VAR
[11] WDFILE+ASSIGN 'WORDS.IFR/DA'
[21] RAND+RPERM[FSIZE+WF[11]
[31] ITEMNO+0+0
[41] WL+WPC[21]
[51] WORDS+(0,WL)*P'
[61] NEXT:+DONE IF 0=PRAND
[71] ITEM+1+RAND
[81] RAND+1+RAND
[91] V+BFITEM[WDFILE
[101] WD+WL+V
[111] VARS+WL+V
[121] +NEXT IF VARS WITHIN RANGE
[131] WORDS+WORDS,[11]WD
[141] ITMNO+ITMNO,ITEM
[151] +DONE IF NW≠P+ITMNO
[161] +NEXT
[171] DONE+DEASSIGN WDFILE

▼ R+ALL X
[11] R+ALL/X

▼ R+ANY X
[11] R+V/X

▼ F+ASSIGN FILENAME
[11] F+DASS FILENAME

▼ TIME+DAYTIME
[11] TIME+I20

▼ DEASSIGN F
[11] QDAS F

▼ XY DISPLAY BUFFER
[11] MACHINE DEPENDENT
[21] DISPLAY BUFFER LINE AT SCREEN LOCATION (X,Y)
[31] D+BUFFER

▼ GOTO+LABEL IF CONDITION
[11] GOTO+LABEL*1CONDITION

▼ IFR
[11] BEGIN
[21] LOOP
[31] WRAPUP

▼ ITM+STR MATCH LIST+R+L
[11] R+STR SIMLIST LIST
[21] ITM+1+R
[31] ITM+ITM*(R[ITM]≥0.7)

▼ ORD+R MESH F+V+Z
[11] V+RPERM((PR)P0),(PR)P1
[21] Z+R,(RPERM F)
[31] ORD+Z+V+Z

▼ INP+PROMPT STRING
[11] D+STRING
[21] INP+D

▼ R+RPERM X
[11] R+X[1(PX)*1(PX)1]

▼ X+1SINCE START
[11] X+((DAYTIME)-START) 60

▼ Z+1 WITHIN R
[11] R+CALL V+R[11]X+CALL V+R[11]

▼ LOOP EF+ORDER+RESP+TRIAL+TYPE
[11] NT+EP[11]+NW+EP[21]+TYPE+EP[31]
[21] ITIME+EP[41]+RTIME+EP[51]
[31] TRIAL+1
[41] SCORE+(NW,0)*0
[51] NEXT:ORDER+SCORE SHUFFLE(TYPE,NW,TRIAL)
[61] CLEAR
[71] 'AA TRIAL '+TRIAL+' AA',DELAY 2
[81] WORDS PRINTWDS(ITIME,ORDER)
[91] DISTRACT
[101] RESP+RESPOND RTIME
[111] RESP+RESP[11]WL
[121] SCORE[TRIAL]+WORDS GRADE RESP
[131] +NEXT IF NT+TRIAL+TRIAL+1

▼ ORDER+SCORE SHUFFLE TWT+S+REC+IGT+TYPE+NW+TRIAL
[11] TYPE+TWT[11]
[21] NW+TWT[21]
[31] TRIAL+TWT[31]
[41] +A2 IF TRIAL-1
[51] ORDER+RPERM(INW)
[61] +0
[71] A2:S+SCORE[TRIAL-1]
[81] RFC+(0+S)/1PS
[91] REC+REC+(0+S)/S
[101] FGT+(0+S)/1PS
[111] +(TYPE-1,2,3)/T1,T2,T3
[121] T1:ORDER+RPERM(INW)
[131] +0
[141] T2:ORDER+REC,(RPERM FGT)
[151] +0
[161] T3:ORDER+REC MESH FGT

▼ S+DELAY NSEC
[11] S+(NSEC/CPS)*IDLE

▼ WORDS PRINTWDS IORD+K+I+ORD+ITIME+XY
[11] ITIME+1+IORD
[21] ORD+1+IORD
[31] XY+ 3 30
[41] CLEAR
[51] K+0
[61] NEXT:+DONE IF (IORD)<K+K+1
[71] I+ORD[K]
[81] BUF+WORDS[I+1],(DELAY ITIME),CLEAR
[91] XY DISPLAY BUF
[101] +NEXT
[111] DONE:+0

▼ DISTRACT NSEC+ANS+DST+NUM
[11] CLEAR
[21] DST+DAYTIME
[31] D +'ADD THE FOLLOWING NUMBERS:'
[41] LP:+RETURN IF NSEC<TSINCE DST
[51] NUM+? 10 10
[61] IN:ANS+PROMPT('NUM[11]','+',(NUM[21]),'='
[71] +OK IF(+/NUM)=ANS
[81] +INFO +WRONG, TRY AGAIN'
[91] OK:+LPID +RIGHT'
[101] RETURN:+0

▼ R+RESPOND RTIME+IN+L+NR+RSTART
[11] CLEAR
[21] D +'AA RECALL AA'
[31] L+20
[41] R+'
[51] RSTART+DAYTIME
[61] MORE:+OVER IF RTIME<TSINCE RSTART
[71] IN+D
[81] +DONE IF IN+L='/'
[91] R+R,L+IN
[101] +MORE
[111] OVER:ID +'RECALL PERIOD IS OVER'
[121] DONE:ID +'END OF TRIAL'
[131] NR+(PR)-L
[141] R+(NR,L)PR

▼ SV+WORDS GRADE RESP+NW+K+V+N+LOC+LN
[11] NW+1+PWORDS
[21] SV+(2+NW)*0
[31] K+0
[41] NEXT:+0 IF (1+PRESP)<N+K+1
[51] W+RESP+J
[61] LOC+WORDS[A+V
[71] LN+LOC+1
[81] +FOUND IF 1=ANY LOC
[91] CSPELL:+FOUND IF 0=LN+W MATCH WORDS
[101] +INTR
[111] FOUND:+CORRECT IF 0=SV[LN]
[121] +REP
[131] CORRECT:SV[LN]+K
[141] +NEXT
[151] INTR:SV[1+NW]+SV[1+NW]+1
[161] +NEXT
[171] REP:SV[2+NW]+SV[2+NW]+1
[181] +NEXT

▼ WRAPUP
[11] PUTRESULTS
[21] SUMMARY
[31] PRINTREPORT
[41] SIGNOFF

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