SESSION I PRESIDENTIAL ADDRESS

The influence of computers on psychological research: A case study

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Computers are pervading all aspects of the research process: literature search, experimental control, recording of results, storage of data, analysis of results, development of theory, data-theory comparison, preparation of figures, and preparation of manuscripts. This article describes the influence of computers on a single experimental study, one in which physostigmine is found to affect the memory of rats for time intervals. The computer methods used are compared with other methods currently available. Some speculations are made about the influence of computers on research when networks are more fully developed.

Computers have been used extensively in all of my research during the last 10 years. To provide a concrete illustration, I will describe a case study. The case study is a single experiment from a series of experiments that Warren Meck and I currently have in progress on the influence of various psychoactive drugs on animal timing, memory, and decision processes.

THE INFLUENCE OF THE COMPUTER AS A MODEL OF BEHAVIOR

The major effect of the computer on this research project was as a general-purpose device that could do the jobs of many special-purpose devices and do them better. It has also had another effect in psychology: It has served as a model of an intelligent mechanism, one that might apply to animals or human beings. In the development of a theory of timing, we were not immune to this influence.

John Gibbon and I have described an information processing representation of scalar timing theory that is closely related to the one presented by Triesman (1963). The top row of Figure 1 shows the clock process, the second row shows the memory process, and the bottom row shows the decision process. The general notion is that there is an internal pacemaker that puts out pulses that can be switched into an accumulator. The contents of the accumulator go to working memory, where the signal duration on a given trial is stored. The reference memory contains a representation of previously reinforced signal durations. The signal duration in working

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Figure 1. An information processing model of timing. The top row shows the clock process, the middle row shows the memory process, and the bottom row shows the decision process. (Adapted from Gibbon & Church, in press.)

memory is compared with a signal duration in reference memory. If, with a relative response rule, it is close enough, a response will be made. Gibbon and Church (in press) have shown the effect on performance of variability in the pacemaker, switch, memory, and threshold for response, taken one at a time.

This model is certainly computer-like, with respect to both hardware and software. Its parts are like hardware components of a computer. There are clocks, switches,

accumulators, temporary and permanent storage devices, and comparators. We have taken some of these analogies seriously, and they have guided our thinking. For example, if a rat has an internal clock, we have assumed that it will have many of the properties of some man-made clocks (Church, 1978; Roberts, in press; Roberts & Church, 1978). On the basis of various experimental tests, we concluded that the internal clock used by rats for estimating times in the second to minute range has many of the same properties as a stopwatch. For example, it times up rather than down, it times on a linear scale, it can be stopped and continued from where it ended, it can be reset, and it has an internal pacemaker. By taking the analogy seriously, we have conducted tests that otherwise we probably would not have considered. Of course, it is important not to allow the analogy to constrain one's thinking, since it is possible that some of the properties of the timing mechanism used by animals would not be found in a computer. For example, Meck (in press) has discovered that a drug can produce a proportional distortion in the remembered duration.

Our information processing model of timing is obviously related to a computer program. Figure 1 shows the model as a flow diagram. It consists of separate modules that are interrelated to perform a specific task. The output of the program (a response) is determined by the input to the program (signal duration on the current trial and conditions of reinforcement on previous trials). One of the virtues of thinking of the timing model as a computer program is that it forces a complete and precise statement of the theory. A well specified model can be simulated in an unambiguous way. Models based upon an analogy to a computer program normally have serial processing and functional localization, but this certainly is not required at the conceptual level. From some points of view, a timesharing system can be thought of as one that involves simultaneous parallel processing of multiple jobs and distributed resources.

THE CASE STUDY: THE EFFECT OF PHYSOSTIGMINE ON TIMING BEHAVIOR

The procedure that we used in the case study was the "peak procedure." The properties of the peak procedure have been well explored by Roberts (1981, 1982). Figure 2 shows the median results from 10 rats trained extensively on a 50-sec peak procedure (Meck & Church, in press). After a 130-sec intertrial interval, a houselight signal began. On a random half of the trials, food was available after 50 sec and the first response after that time led to the delivery of a pellet of food; on the remaining trials, no food was available and the signal remained on for 130 sec. The number of responses in each 1-sec interval was recorded on each trial for each rat. Averaged across trials and rats, the median response

Figure 2. Results from the peak procedure. Median responses per minute as a function of time since the trial began. On half the trials, reinforcement was delivered following the first response after 50 sec.

rate increased as a function of the time since a trial began to a maximum near the time that food was sometimes available (50 sec), and then it declined in a fairly symmetrical fashion on a linear time scale.

The smooth function near the data points is the fit of a scalar timing model developed by Gibbon (Church & Gibbon, 1982). A closely related model was used for the case study. Clock speed and a decision threshold are random variables. A ratio proximity rule is used to decide whether or not a response was made; if the clock is close enough to the remembered time of reinforcement, a response was made. Applied to Figure 2, with three free variables (clock speed, threshold level, and threshold variability), the theory accounts for 99.8% of the variance in the data, the values of the parameters (.15, .25, and .30) are similar to those previously obtained, and there are no large systematic deviations of the theory from the data: There are 48 runs of the theory relative to the data; 50 is the expected number.

In previous research, drugs that changed the effective level of the neurotransmitter dopamine changed behavior in a manner that could be interpreted as changing clock speed in a corresponding manner (Maricq & Church, in press; Maricq, Roberts, & Church, 1981; Meck, in press). This research used both the peak procedure and a very different timing procedure, a bisection procedure. With the bisection procedure, Meck found that drugs that changed the effective level of the neurotransmitter acetylcholine changed behavior in a manner that could be interpreted as changing memory storage speed (Meck, 1983). One purpose of the present experiment was to determine whether changes in the effective level of acetylcholine would have similar effects on the peak procedure. It is important to know that we are studying the effect of drugs and neurotransmitter systems on basic psychological and physiological processes, not just on behavior in a particular procedure.

Thus, it is important to reach similar conclusions based upon very different timing tasks.

THE INFLUENCE OF THE COMPUTER AS A GENERAL-PURPOSE DEVICE

In research reports, investigators rarely report the details of the computer techniques employed. In recent years, I have often put a single sentence in the apparatus section, such as "A timeshared PDP-12 computer controlled the experimental equipment and recorded the responses." I occasionally have referred to a software package that was used, but the reader would have no basis for knowing whether or not computers were used extensively in the research reported. This is appropriate for a report on the substance of the research. For this purpose, one wants to know the background of the research (the introduction), what was done (the method), what was found (the results), and how the results might be explained (the discussion). For a reader interested in the substance of the research, it is not important to know how the procedure was implemented, what device was used to analyze the data, and so on.

For those of us interested in research methods and instrumentation, however, the computer methods employed in research are a focus of interest. Computers are now involved in all aspects of the research process. This process consists of at least nine distinct activities, as shown in Table 1. Nine research activities are listed in the left column. An example of a special-purpose device to assist an investigator in conducting each of these activities is listed in the right column. A special-purpose device can be used only for some research activities. Results can be analyzed with a calculator, but not with a reference book; manuscripts can be prepared with a typewriter, but not with a calculator. In contrast, a computer is a general-purpose device: It can be used for all aspects of the research process.

Initially, computers were used in psychological research primarily for analysis of data. This was normally done on large computers, either in batch mode or, later, in an interactive timeshared mode from a remote terminal. The development of the LINC computer

provided a new perspective on computers (Clark & Molnar, 1964). They were seen as laboratory instruments, primarily for control of experiments and recording of data, but also for storage of data, analysis of results, development of theory, and comparison of data with theory. Libraries subsequently were able to offer facilities for key-word searching of journal titles and abstracts, and both large timeshared computers and small microprocessors developed facilities for the preparation of figures and manuscripts.

In the present case study, we used computers for all these research activities, but different ones for different activities. One computer was used for search of the literature, a DEC PDP-12 was used for control of the experiment and recording of results, a DEC PDP-11/V03 was used for the storage of the data, analysis of results, development of theory, and comparison of data and theory, a different DEC PDP-11/V03 was used for the preparation of figures, and a Zenith Z-89 was used for preparation of the manuscript.

Many different software systems were used in the various research activities. These included a software system for search of the literature, a locally developed language (THICIE) for control of experiments and recording of results, PDP-8 and LINC assembly language programs to transfer data from the PDP-12 computer to the PDP-11 computer, PDP-11 assembly language with RT-11 macros to accept the transfer of data, BASIC for analysis of results, development of theory, and comparison of data and theory, a locally developed package for preparation of figures (GRAPH), and AUTOSCRIBE for word processing.

Literature Search

One method of finding previous research on a particular subject is to conduct a year-by-year examination of certain reference books, such as *Science Citations*, *Indicus Medicus*, and *Psychological Abstracts*. Another is to use the terminals in the library that can access such data bases. Although we have not yet begun a serious or imaginative search of the literature, we have made a search of *Psychological Abstracts* dealing with the role of acetylcholine in memory. The information in *Psychological Abstracts* since 1967 is available in computer files, and one can search for such key words as "acetylcholine" or "memory" in the title or abstract. There were 576 references to "acetylcholine" and 15,307 references to "memory." There were only 28 references to both acetylcholine and memory, so we requested that these references be printed out on the library terminal. Normally, we would examine only a few and then have the complete references with abstracts printed at the site of the computer and mailed. This produces collections of abstracts, many of which are relevant to the topic. The references and abstracts are accurately transcribed, neatly copied, and systematically identified. Alternative search methods are often haphazard.

Table 1
Examples of Special-Purpose Devices for
Various Research Activities

	Research Activity	Special-Purpose Device
1	Search of Literature	Reference Books
2	Control of Experiment	Relay Circuits
3	Recording of Results	Counters
4	Storage of Data	File Cabinets
5	Analysis of Results	Calculator
6	Development of Theory	Books of Tables
7	Comparison of Data With Theory	Graph Paper
8	Preparation of Figures	Lettering Sets
9	Preparation of Manuscript	Typewriter

Many drugs interfere with performance, and it is usually not clear why they did so. Did they make the animal sick, fearful, inattentive, or forgetful? Or did they alter motor performance? Anticholinergic drugs, such as atropine and scopolamine, interfere with performance. One possibility is that cholinergic mechanisms are required for learning and memory.

Some drugs improve performance, and these are particularly interesting, for both practical and theoretical reasons. Physostigmine acts against the enzyme that breaks down acetylcholine, acetylcholinesterase. Thus, it increases the amount of the neurotransmitter acetylcholine available in the synaptic cleft.

What did Meck and I expect to happen if physostigmine were administered to an animal performing on the peak procedure? Based on the literature, physostigmine should increase the effective level of acetylcholine and improve memory; based upon Meck's (1983) conclusions from another timing procedure, physostigmine should decrease the variability of some internal process and decrease the remembered time of reinforcement. This would produce a narrower peak function that would be shifted to the left on the time scale.

Experimental Control

The subjects in the experiment were 20 male albino rats. They all received intraperitoneal equal-volume (.2-cc) injections of saline or of .15-mg/kg physostigmine salicylate on alternate days. Half the rats were trained only on days on which they received the drug (the physostigmine group); the other half of the rats were tested only on days on which they received saline (the control group). This design, previously developed by Meck (1983), ruled out any general effects of repeated doses of the drug, since all subjects received equivalent injections; the only difference between the subjects was whether they were trained following physostigmine or saline injections.

The rats were trained in standard lever boxes located inside a sound-attenuating chamber. Each of the 10 lever boxes has a retractable lever, a food dispenser, a house-light, and a speaker. Thus, equipment must detect switch closures produced by the levers, control the motors that insert and retract the levers, operate the solenoids that dispense food, turn on and off the houselight, and switch the output of the white-noise generator to the speaker.

The procedure was as follows: Ten rats were trained simultaneously. After a 2-min intertrial interval, a signal was turned on. On half the trials, randomly selected, 20 sec after signal onset, a food pellet was available to be delivered immediately following the next lever response; on the remaining trials, no food was available. When food was delivered or when the signal had been on for 50 sec, whichever came first, the signal was terminated and the trial ended.

This would not be a difficult procedure to instrument with relay equipment. The circuitry is not complicated, but there would be lots of it. To control 10 boxes asynchronously, it would be necessary to have 10 duplicate systems (i.e., 10 stepping switches, etc.). The system controlling the experiment was a DEC PDP-12 computer with a real-time timeshared software system developed by Dyckman and Church (1972) called TIICIE, a "timed interpretative system for interactive control of independent experiments."

With this system, it is possible to conduct many experiments simultaneously. Such timesharing has been essential for the efficient operation of a computer in our laboratory. It is much more efficient to test 10 subjects simultaneously than successively. Although the TIICIE system permits independent, interactive control over each experimental box, these capabilities have seldom been used. Typically, an investigator uses all 10 boxes simultaneously without interactive control or monitoring the performance of the subjects.

Simple instructions are available to deal with all inputs from our experimental equipment and all outputs to our experimental devices. No hardware modification is necessary to record from, or to control, any existing device. We continue to find it easy to implement any experiment that uses the equipment that is currently interfaced to the computer, but it is time-consuming to modify the equipment. The user's programs for the control of experiments and recording of results are easy to prepare. Programmers experienced in other languages find it relatively easy to learn TIICIE, since there is a good reference manual. This is a worthwhile activity only for those who plan to use the system for more than one or two experiments.

The main limitation of the system is that it is based on a polling procedure, and the typical rate of polling is only 10 or 20/sec.

There are several advantages of a computer over relay circuits for control of our experiments:

(1) It is a neat package—The necessary computer equipment to control experiments normally occupies much less space than that required by alternative devices.

(2) Ease of modifications—When a standard relay apparatus is set up for a particular experiment, there is great reluctance to change it to conduct another experiment if there may be some further use of the previous configuration. An MAC panel permits such change, but extensive program modification is accomplished more efficiently with a computer program. With a computer, various procedures may be conducted at different times of day in the same boxes; all programs to control experiments can be saved on magnetic tape.

(3) Error reduction—After a computer program has been debugged, failures are exceedingly rare. With relay equipment, a contact can fail, a wire can be dislodged, and so on. With a computer program, there can be documentation of the procedure actually implemented, and

the actual program can be kept indefinitely. Although a wiring diagram of a relay circuit can be kept permanently, the wiring diagram may not accurately represent where the wires are located.

(4) Necessity—For some purposes, such as rapid interactive control and complex stimulus displays, a computer may be the only equipment that can accomplish the task. In my original request for a computer as an equipment grant from the National Science Foundation (NSF), this was the kind of procedure I emphasized. In fact, this situation has rarely arisen in our laboratory.

In my original equipment request for the PDP-12 in 1971, I predicted a 10-year use for the computer. It is likely to continue to control experiments much longer. Last year, we received a gift of an abandoned PDP-12 that will be used for replacement parts; this should further extend the life of our current system. More modern computers have much better operating systems, they have much more memory, they are somewhat more reliable and much less expensive, they use less energy, and more people know how to fix them. As long as the old computer continues to do the job, it is not wise to spend the time or money to change the system. A new computer can replace the functions of an old one, and it can be integrated with the old one, or it can be added to perform new functions. Gradualism is a reasonable principle so that equipment modifications do not take unreasonable amounts of time from research productivity.

Because of the cost of computers in 1971, we assumed that control of 10 or more experiments required the timesharing capabilities of a minicomputer. Now, an inexpensive microprocessor with timesharing software or separate microprocessors attached to each chamber are realistic alternatives. The latter has advantages in repair and simpler software. Whether a single computer is used with timesharing software or separate computers are used with each chamber, the ability to test multiple subjects simultaneously has continued to be essential to efficient operation of our laboratory.

Recording of Results

A record was required of the number of responses in each 1-sec interval, summed across trials. To record the number of responses that occur during 1-sec intervals for 50 sec, a rotary timer geared to depress a micro-switch at 1-sec intervals could drive a 50-position stepping switch. Each response would activate a relay with a resistor-capacitor circuit to gate the response through the stepping switch. It would be necessary to have 50 counters for a single animal. To test 10 animals simultaneously, 500 counters would be required. More would be required for different trial types (food vs. nonfood, light vs. sound), and many more would be required for trial-by-trial analysis. This is not practical. It would be expensive to purchase, be time-consuming to wire and to read, occupy lots of space, and so on. A

mechanical printing counter is not a reasonable solution, since it could print the number of responses each second of each trial, but later hand analysis would be required to combine trials.

In our original description of the requirements for the computer system, we recognized that it must be possible to record extensive data on magnetic tape during an experiment, and the data should be in a form that could readily be analyzed. The facility to store data on tape during an experiment has been essential. In TIICIE, there is an instruction, "DATA," that puts a four 12-bit word entry into a double buffer for subsequent writing onto magnetic tape. The four words are referred to as N, W, X, and Y. In the present experiment, the left 6 bits of N were used to identify the subject and the right 6 bits were used to identify the type of trial (sound or light); W was used to identify the trial number, X was used to record the number of responses, and Y was used to record the number of seconds since the trial began (1-50). Thus, a four-word entry was made for each second during which at least one response occurred for each peak trial. Entries for the various subjects were written in the order in which they occurred, but since each entry was identified, it could be sorted later.

In addition, it should be possible to print data during an experimental session and immediately after the session. It is convenient to print out summary data at the end of a session, but only occasionally has it been useful to examine data during a session (see Church, 1973, for a description of seven types of data).

Although complicated experimental control was the original major justification for a computer in our laboratory, recording of data has been more important. Some investigators spend most of the time in planning experiments; others spend most of the time in apparatus development, others in theory development, and others in preparation of manuscripts. In recent years, most of our time has gone into analysis of results, which requires a large available data base.

Of course, magnetic tape as the major mass storage device is not what would be currently chosen. Probably 8-in. floppy disks are the dominant medium in most laboratories, but, again, it is not wise to spend the time or money to change a working system.

Storage of Data

Data should be stored for long periods of time in a form that is convenient for analysis. Thus, it is much better to have the data in some computer-readable form than printed on paper. Our data were on magnetic tape, a form convenient for data analysis on the PDP-12 with a higher level language, such as FOCAL. Unfortunately, at any given time, this computer had to be used either for the control of experiments and the recording of data or for the analysis of data. We did not have an operating system that permitted data analysis in the background

while experiments were conducted in the foreground, and there was no space to add such a capability. The computer had only 8K words of memory, and that was required for real-time control and recording. Additional memory was expensive and not easy to install. Since it was usual to test animals for 16 h/day or more, it was desirable to find an alternative way to analyze the data. It turned out to be less expensive to purchase a new computer than to upgrade the old one. Therefore, we purchased the PDP-11/03. The data were recorded initially on magnetic tape but were transferred to the floppy disk of the PDP-11. The two computers were connected with a 9,600-baud serial interface. In this application, the PDP-11 became a peripheral device to the PDP-12, and the two computers can be regarded as a single system. An assembly language program was written to move data from tape to the core of the PDP-12, and another assembly language program (with RT-11 macros) was written to move data from core of the PDP-11 to disk. Thus, each 12-bit word from the one computer is transferred to a 16-bit word of the other computer, and checksums are transmitted to guard against transmission errors.

The floppy disks of the PDP-11 have been the major long-term storage device for data. This has been convenient, since the data analysis has been done on the PDP-11. In the future, we may want to use the larger disks of departmental, center, or university computers for long-term storage. The disks, printers, and other expensive peripheral devices cannot be duplicated in any single research laboratory. The main problem is that communication from our computer to the others must be developed. In principle, this could be done with floppy disks, modems and telephone, or a broadband cable that will be described later.

Analysis of Results

We are now ready to examine the data from our experiment. For each rat for each day, we calculated the number of responses in each second since the trial began (Seconds 1-50) and counted the number of trials to determine the response rate as a function of time. This was done separately for the two signals, light and sound. Only the results for the sound signals are shown here. The median was then calculated for each rat over 5 days, and the median function was calculated for the 10 animals in each group.

The results are shown in Figure 3. In the saline group, the response rate increased as time in the trial progressed. It reached a maximum at 20 sec, the time at which food was sometimes available, and then it declined. In the physostigmine group, the response rate also increased to a maximum and then decreased. But there are two differences. The rise and fall were steeper and, more remarkably, the peak of the function was about 16 sec, much earlier than the time food was actually available. This was a strange result, but, as you recall, it was anticipated.

Figure 3. Data: Median responses per minute as a function of time since the trial began for rats receiving physostigmine (left panel) and saline control (right panel). On half the trials, reinforcement was delivered following the first response after 20 sec.

The present analysis is simple and direct. It could have been done without a computer, although it would have taken much longer to complete. Modern electronic calculators are much superior to the mechanical rotary calculators used previously, but any analysis is tedious if extensive data must be entered by hand, especially if data must be entered several times. Other analyses that we have done on data of this sort, such as trial-by-trial identification of the location of the peak, involved analyses that would require so much time to complete by hand that they probably would not have been done without a computer. The use of a computer for the analysis of data also has made it feasible to use exploratory data analysis techniques.

For the analysis of the results of the present experiment, and most other experiments, we used the PDP-11. Initially, BASIC was the only higher level language available, so we developed subroutines in this language for graphical displays, formatting, and other general purposes. Later, we purchased other higher level languages (PASCAL, APL). Although other languages are better for structured programming, amount of code, speed of execution, and so on, there is great inertia since any change requires effort that would distract us from our research.

For analysis of results, there were many alternative computers that could have been used: It would be possible to use the computer that controlled the experiment (the PDP-12), the system to which the data were sent (the PDP-11/03), a departmental computer that had more memory, more disk storage, and more speed (a PDP-11/23), a much larger computer in the Center for Cognitive Science (a VAX-11/780), or a still larger university computer (an IBM 4341). The available software and peripheral devices improve as one moves from the computer in our laboratory to the one in the department, to the one in the center, and to the one in the university. We used the small computer in our laboratory, since it was easiest to get the data to it, the computer was always available, and there were good interactive graphics attached to it. Such a small computer, however, does

have limitations: The software is limited and execution time is slow. In the near future, we will use the network to be described to connect the laboratory computer with the VAX in the Center for Cognitive Science. This will provide the advantages of both a dedicated small computer and a large timeshared system.

One advantage of data analysis by computer is that the user has confidence that the results are accurate. To validate a program, for either data analysis or administration of a procedure, it is desirable to have test data produce identical results when put through programs written by two different programmers in two different languages (Roberts, 1980).

Development of Theory

For the present experiment, we assumed only two sources of variance: the pacemaker and the threshold. The process works as follows: On a given trial, the pacemaker puts out pulses with some mean and standard deviation. The ratio of the standard deviation to the mean is the coefficient of variation, γ . Reinforcement was available on some trials at 20 sec. The value in working memory at the time of reinforcement is stored in reference memory. On each trial, a threshold is determined that is a random sample from a normal distribution with mean B and standard deviation σ_b . A measure of proximity is calculated: the absolute difference between the value in working memory and a random sample of the value in reference memory, divided by the value in reference memory. If that value is less than the sampled threshold, a response is made; otherwise, no response is made.

This process can be simulated by hand, but it is a very time-consuming process. The Rand (Rand Corporation, 1955) volume of 1 million random digits, particularly the 100,000 random normal deviates, is helpful. Each calculation involves two random normal deviates and some arithmetic operations. It is necessary to take hundreds (preferably thousands) of samples at each of the 50 points on the function, and this must be done for each combination of the parameters to be examined. Of course, a computer is an ideal device for such a simulation program. We have implemented such a program on the PDP-11 in BASIC. The input is the value of the parameters and the number of samples, and the output provides statistics of goodness of fit and a graphical display. The ability to simulate has allowed nonmathematical psychologists an opportunity to explain data in a quantitative manner, and it has helped mathematical psychologists derive closed expressions by providing some information regarding the function form and by providing checks. It also has allowed mathematical psychologists to determine quickly what models might be worth rigorous analysis.

John Gibbon has been able to derive closed expressions for these results, so that simulation is not required (Gibbon & Church, in press). The closed expressions produce smoother, more accurate theoretical functions, and

Figure 4. Theory: Response probability as a function of time since the trial began. The family of curves in the left panel represents changes in variability of clock speed (γ); the family of curves in the right panel represents changes in threshold variability (σ_b).

the functions are available in seconds rather than minutes. We have two versions of BASIC programs that include these equations. In one version, the operator puts in the values of the parameters; in the other, the computer does a systematic search of the parameter space between limits, with a resolution supplied by the operator. In both cases, the output provides statistics of goodness of fit and a graphical display. The capacity to search systematically or exhaustively the parameter space is a major value of a computer in the development of a theory.

Figure 4 shows what happens to the probability of response given attention to the stimulus as a function of time since the trial began. The functions are normalized as a percentage of maximum. The left set of functions shows this function with variations in variability of clock speed (γ) and no threshold variance. As clock speed becomes more variable ($\gamma = .1, .3$, and $.5$), the function becomes more variable and more asymmetrical. The right set of functions shows what happens with variations in threshold variability ($\sigma_b = .1, .3$, and $.5$) and no clock variance. The function becomes more variable in a symmetrical fashion. In all cases, the most probable response is close to the reinforced value, 20 sec.

With closed expressions available, the consequences of variations in any single source of variability and of any combination of sources of variability can be explored quickly and accurately. With experience, one learns what can be achieved by which combinations and what cannot be achieved.

Comparison of Theory to Data

For the development of the theory, many different computers could have been used: the one in my laboratory, the department, the center, or the university. Even the one in my office (a Zenith Z-89) could have been used. When it is time to compare theory to data, however, it is highly desirable to use a computer to which the data can be readily transferred.

For this reason, we used the PDP-11 that had a DEC VT-55 terminal with limited graphics capability. A given

Figure 5. Comparison of data and theory.

visual comparison of theory and data is more valuable than tables and statistics, particularly in the early stages of development of the theory.

Figure 5 shows an application of scalar timing theory to the results from the case study. The experiment is not yet complete. With fewer days to analyze than usual, the functions are not as smooth, so the theoretical fits cannot fit as well. These preliminary fits account for slightly over 95% of the variance, but there should be further improvements before the experiment is complete. The same coefficients of variation of the clock and standard deviation of the threshold were used in both cases (.3 and .5), but there were two differences. The physostigmine group had a lower threshold (.2 vs. .6). This means they withheld responding longer into the interval and, more interesting, that the mean remembered time of reinforcement was 16 sec rather than 20 sec. This suggests that the representation of the signal duration stored in reference memory following reinforcement was about 20% less than the representation of the signal duration in working memory.

Preparation of Figures

For the preparation of a manuscript, I usually begin with the methods section and then the results section. The introduction and discussion are done last.

For the results section of a manuscript, I usually like to start with rough drafts of the figures. They provide the outline of the story to be told. Previously, we used one of two methods for preparing final drafts of figures: pen and ink or lettering sets. I have always felt uncomfortable with lettering sets because of increasing concern of making an error as the figure nears completion. Errors can be corrected, but the corrections are time-consuming and never perfect. The process of making the graph is onerous, particularly for individuals who do not make a lot of them and if all equipment is not in place and kept neat and clean. Thus, many of us turn to more professional draftspersons, and this is expensive. An alternative is to use paste-down letters. Errors are much less likely with this process, but it is slow. With either method, minor adjustments, such as a change of the symbols used for the data points or a rescaling of one of the axes, often require that the entire figure be redone.

Several different computer systems for generating graphs were available: a Calcomp plotter attached to the IBM at the university computer center and a Tektronix graphics system being developed for the Center for Cognitive Science computer. However, I chose to use the one in a colleague's laboratory. He has interfaced a Houston Hi-Plot X-Y plotter (at less than \$1,000) to a PDP-11/03, and a graphics package has been written in BASIC (Hayes, 1981). The system is less versatile and slower than some of the alternatives, but it is the most compatible and available. Figures 2-5 were drawn by this computer system; Figure 1 was generated on a Tektronix graphics system attached to a PDP-11/34.

Preparation of Manuscript

In the preparation of a manuscript, some individuals use pen and paper; others use dictating machines, and others use typewriters. For those who use an electric typewriter, the repeated "X" key is particularly useful in editing. Other editing can be done with pen or pencil. Rearrangement of paragraphs can be done with scissors and a stapler. Unfortunately, all this leads to a messy document. Since I have had the luxury of secretarial assistance, I have been bringing messy documents for a "clean draft." This has not been entirely satisfactory for several reasons: (1) Since the revision of a manuscript has a lower priority than several other secretarial activities, there often was a long gap between the submission of the material and the return of the clean draft. This interrupted the normal flow of ideas. (2) Since human typists get bored, and sometimes irritated, by seeing the same document too many times, I felt uncomfortable asking to have more than two or three drafts of a document typed. (3) I often worked with a messy draft because I did not want to take the time to get a clean draft, and I did not want to use up the total number of drafts I could ask a typist to do. (4) In a retyped manuscript, new typographical errors often appeared in sections that had been accurate and were not changed editorially.

In recent years, all my manuscripts have been prepared on a word processing system, and that includes the text of this manuscript. The most important aspect of any word processing system is that it permits the writer to have an updated revision at any time.

The manuscript was prepared on a Zenith Z-89 microprocessor with Zenith's Autoscribe software system and an NEC Spinwriter output. It may be interesting to note why I chose this system over other systems that were available to me. I could have used the PDP-11 in my research laboratory, with the TECO editor and RUNOFF formatter and a DECwriter output, an IBM personal computer in my teaching laboratory, with the UCSD PASCAL editor and an Epson printer, and/or the university IBM 4341 computer, with the SCRIPT word processing system and printed on either a laser or Diablo printer in the computer center. Zenith Z-19 terminals are available in my home, office, and laboratory and in departmental and university terminal

rooms. My main consideration was convenience: I much preferred to use a system that was located in my office or my laboratory to which I had guaranteed access at any time, with faster response time. My secondary consideration was to have typewriter quality output that could be used for journal submission without retyping. This led me to choose the Zenith system in my office. This was particularly convenient, since my secretary and I both have the same system so that we can both work on the same disks. The choice was not controlled by the quality of the software available. For routine purposes, all of the word processing software systems were satisfactory. The one I chose was undoubtedly the worst system in terms of number of options available and the number of incompatible symbols used to achieve the same functions in different environments.

By using a word processing system that permits numerous revisions, I am convinced that my manuscripts are prepared more quickly, they contain fewer typographical errors, and they are clearer.

CONCLUSIONS AND SPECULATIONS

In this case study, and in most of my research, computers served in place of special-purpose devices. They served as effective substitutes for reference books, books of tables, relay circuits, banks of counters, calculators, graph paper, lettering sets, and typewriters. Computers were used at every stage of the project: introduction, method, results, and discussion, and in the preparation of the research report.

All of the applications of computers to the research process that have been described are used widely and routinely; none of them was required for the success of the research. Still, the impact of the computer on the research was enormous. Our experience is not atypical. In this case study and, perhaps, in all of my research, the computer facilitated the work on some quantitative dimension (e.g., increase in speed, decrease in errors). A sufficiently large quantitative improvement, however, leads to a qualitative change, since some projects that would not have been undertaken were successfully completed.

Many different computers and many different software packages could have been used to accomplish many of the tasks (e.g., word processing, preparation of graphs, statistical analysis). They may be categorized as computers operated by the university, the center, the department, and the laboratory. As one moves from the computers operated by the university to those operated by our laboratory, there is a reduction in capability and in software. There is more hands-on use and immediate feedback if a laboratory-based computer is used. One person does all on a laboratory computer; at the university level, there are different specialists for different software packages.

In the case study, five different computers were used and many different programming languages. My choice was based primarily upon availability. I do not believe there was a single case in which the choice was based upon the inherent advantage of a particular computer or particular language. Technical superiority is an important issue at the time an investigator decides whether to buy one computer or another, or whether to implement one software system or another. But when one system is working on a particular computer that is available to an investigator, the choice has already been made. In most cases, it is simply not worth the effort to implement a better system for a particular project.

How do I expect the situation to be different in the next few years? These expectations can be formulated on the basis of extrapolation of present trends or upon an analysis of needs. Computing in psychology has been changing rapidly. It is possible that the limiting factor to future development may be our inability to formulate new needs.

Although there was some computer and some software system to handle each of the nine stages of the research process, it was necessary to deal with many different systems to complete the job. More compatibility and greater simplicity would be highly desirable. This can be achieved with the development of scholars' work stations connected on a network.

Brown University has installed a 300-MHz broadband (coaxial cable) communication network into 110 buildings on campus. Connections to the network are currently available in many laboratories, offices, lecture rooms, and student dormitory rooms. This network is like a superhighway with total connectivity of all nodes. There are now about 1,000 devices connected to the network.

A wired university of this sort can support distributed processing. The notion is that researchers can work at a scholar's work station that will be a personal computer with high-resolution raster graphics. It is reasonable to speculate that most faculty members, students, and administrators will spend as much as half their working time at such work stations. Many functions will be performed locally, but others will be performed at facilities located elsewhere on the network. Thus, a person working at a single work station with a single operating system can (1) use an on-line library catalog, (2) make literature searches both with key words and with some semantics, (3) examine data from other laboratories, (4) perform exploratory and inferential data analysis, (5) do simulations, (6) compare data to theory, (7) write papers, and (8) send them to editors for review and then to a printer for publication. In addition, the work station can serve various teaching needs. For example, there could be message systems for communication between instructors and students so that assignments could be made and problems and papers could be

submitted, reviewed, and revised. The work station could also serve various administrative needs (e.g., message system, access to data bases). Most of these functions can be accomplished now, but they require the use of many different computer systems, few of which are compatible.

The particular mix of individual, departmental, center, or university computers will be determined primarily by market considerations. There are many disadvantages to overcentralization. Errors are very serious, and a central organization can become committed to its mistakes, so changes are difficult. A large staff is required for maintenance and development of the system and for the training of a large number of users with different levels of knowledge and different requirements. Such an organization can provide service to some subgroups while ignoring the legitimate requirements of others. The era of the computer center that attempts to handle all the computing requirements of all members of a university community with a central facility has ended. Centralization of some special functions, however, will still be reasonable. For example, a university might support a computer system dedicated to mass storage. Distribution of facilities is clearly required for most functions.

Separate computers for various administrative departments and research groups are cheaper, and no large mistakes can be made. This also provides better security. In such a situation, not everyone needs to be a technical expert. One person may lead the way with an initial purchase and development of a system. If it is successful, others will copy the system.

In the present research, I used only computers available as an individual. With the network, there is excellent reason to make use of departmental and center computers with better software.

The development also is dependent upon management decisions. For example, the cost of library searches may depend upon the ownership of the data bases. This is something that might not be feasible for a single university but could be obtained by a consortium of universities.

In addition to the development of networks within institutions, there probably will be an increase in the availability of network connections to researchers at other institutions. The plans for COGNET, a network particularly for cognitive psychologists, is one example (Millward, 1981). The collaborative work that John Gibbon and I have done on timing would have been facilitated by a network connection. In this application, a computer can replace special-purpose apparatus such as a telephone or a train.

Such interconnectedness would encourage the development of libraries of data that would provide common data sets for analysis. This would greatly facilitate the work of mathematical-theoretical psychologists, who would then have access to the detailed aspects of the data of the best empirical studies.

Few of us have all the skills that are required in the

research process. The ideal researcher has a scholar's knowledge of the literature, a bookkeeper's precision in implementing a procedure, a statistician's skill in analyzing results, a mathematician's skill to derive the consequences of a theory, an artist's skill in drawing graphs, and a professional typist's ability to prepare a manuscript. The computer now can help ordinary people act more like a scholar, bookkeeper, statistician, mathematician, artist, and typist.

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