SESSION VII CONTRIBUTED PAPERS: EVALUATIONS OF ON-LINE COMPUTER APPLICATIONS IN PSYCHOLOGY

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The impact of computers on cognitive psychology

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Computer developments and their applications in cognitive psychology are reviewed. Examples from recent studies illustrate the ways that computers are used for different research purposes: stimulus generation, on-line interactive experimental control, response collection, data analysis, and theory building. A quantitative analysis of federal funding for computer-based and noncomputer research compares costs over the past 9 years for the areas of perception, memory, learning, and thinking. A tabulation of journal articles relevant to computer-based cognitive research shows the distribution of articles over various categories of hardware and software development. Finally, the advantages and disadvantages of using computers in cognitive research are evaluated.

HISTORICAL OVERVIEW

In evaluating the impact of computers on cognitive psychology, it is reasonable to begin by examining the past history and trends. The history of computers in cognitive psychology is short and recent—about 25 years. The most striking aspect is the increasing speed with which computers have been incorporated into all phases of cognitive research.

Figure 1 illustrates a "cumulative record" of landmark events in the development of computers and their application in cognitive psychology. The abacus, perhaps the first computing device, was in use some 5,000 years ago. It used a bi-quinary number system that was later used on the console display of the IBM 650. The first mechanical computer was built by Pascal, and a better device was built by Leibnitz in 1673. Charles Babbage designed the first large computer, the difference engine, in England in 1812, to calculate tables of mathematical functions. In 1833, he planned the analytical engine, the forerunner of modern general-purpose computers. Although this machine was never constructed, its design innovation

was the use of preprogrammed sequential control of arithmetic operations. About 50 years later, in 1889, Dr. Herman Hollerith patented the Hollerith punch card, which IBM used when it was founded in 1911. As psychologists, we should note Hollerith's early use of punched data with an automatic preprogrammed machine to tally social and behavioral census data.

The next set of breakthroughs occurred after a 30- to 40-year gap. In the 1930s, Dr. Howard Aiken described the first modern preprogrammed computer, the Mark I automatic sequence controlled calculator, completed in 1944 at Harvard University. It used punched paper tape input and had a memory consisting of thousands of electromagnetic relays. Two years later, the ENIAC (electronic numerical integrator and computer), designed by J. P. Eckert and J. W. Mauchly, was completed at the University of Pennsylvania. Its important contribution was operating speed, achieved by electronic internal operation. Two additional hardware innovations were made in 1945 by Dr. John Von Neumann. He proposed to use binary rather than decimal numbers and to store the program instructions in memory. Until that point, control sequencing was external: dials, cards, paper tape, or plugboards. Memory was used only to store data. By 1949, the EDVAC (electronic discrete variable automatic computer) and the EDSAC (electronic delay storage automatic computer) were built using Von Neumann's principles, as well as memory made with ultrasonic speed mercury-delay lines.

During the next decade, in fact, during the very

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Figure 1. A record of events which, in our opinion, were critical to the development of computers and to their application in cognitive psychology.

next year, computers were applied in cognitive psychology. In 1950, Dr. A. M. Turing wrote a paper discussing thought, intelligence, and learning, and the differences between man and machine in these respects. The marriage between artificial intelligence and computer simulation in cognitive psychology was manifested in A. O. Oettinger's 1952 paper, "Programming a Digital Computer to Learn." That paper presents a computer simulation of "a small child sent on a shopping tour" that incorporates many of our current theoretical concepts of information processing, as well as much of our current jargon to describe this processing. First, Oettinger divided EDSAC's memory into two parts: "one to play the role of the experimental subject . . . and the remainder to serve as an extension of the outside (stimulus) world." He then proceeded to describe psychology simulation "experiments" on this "child machine." This simulated child could "memorize" an input shopping list and later recall or "recite" it on the teleprinter. Further, it could translate the shopping list into behavioral acts. At first, the "child machine" shopped for items in its path of stores in a random trial-and-error fashion. However, the "child machine" could learn in five different ways. It could store information about accessed shops for use on subsequent trips; it was capable of incidental learning about items it passed but didn't buy; it could rearrange its memory into a more meaningful organization; it could determine which memory-scanning methods were appropriate for particular situations; and finally, stored items could be recoded to make direct-access retrieval possible in addition to search processes. Realistically, the "child machine" achieved the ultimate measure of human capabilities by acquiring subroutines for memory-decay and forgetting.

The next set of major developments in simulating human cognitive processes came from the laboratories at Carnegie-Mellon University. In a series of papers beginning in 1955, Newell, Shaw, and Simon conceptualized some theoretically important heuristic procedures in their programs that solved logic problems and played chess. This significant research on thinking continues today at Carnegie in ever-expanding and creative ways. Their major recent contribution is methodological: the development of general-purpose simulation programming languages

for cognitive processes. Such general-purpose languages, as opposed to individual programs, give theorists a new degree of flexibility and speed in implementing their ideas.

Also, during the 1950s, the on-line real-time computer-based laboratory was being developed. At first, these laboratories used analog computers, but by the mid-1960s, digital computers had taken over. In the early 1950s, Dr. Franklin V. Taylor of the U.S. Naval Research Laboratory developed one of the first (analog) computer-based cognitive research labs (Chernikoff, Birmingham, & Taylor, 1955; Birmingham & Taylor, Note 1). Their computers were used to generate moving visual stimulus targets having complex and dynamically changing attributes of position, velocity, acceleration, brightness, and temporal blanking. Stimulus changes could be preprogrammed, or else could be a function of the subject's pursuit or compensatory tracking performance. Once the subjects' abilities and limitations were understood, their performance could be improved by providing them with immediate and ongoing feedback, and by letting the computer take over some of their cognitive activities. In particular, marked improvements were obtained if the computer took over some of the process of integrating the stimulus information over time, and also if the computer helped the subject estimate and predict the stimulus target path several seconds or several minutes ahead of time. Based on that research, computers now aid ship pilots by performing the following functions: unburdening, quickening, feedback, and feedforward.

In the mid-1960s, the first major digital computer labs for cognitive psychology were being developed. The labs were built around various machines, including the IBM-1800, the TX-2, the Digital Equipment PDP-1 and 4, and the Honeywell DDP-116. These early labs included Miller, Norman, and Bregman at Harvard, Restle at Indiana, Uttal at Michigan, Suppes and Atkinson at Stanford, Hayes and Rubenstein at Hanscom Field, Yntema at Lincoln Labs, Licklider at Bolt, Beranek & Newman, Swets at MIT, and Newell, Simon, Green, and Gregg at Carnegie. These early labs were extraordinarily productive for two reasons. First, they were dedicated to turning out high-quality psychological research rather than to developing bigger and better computer

Figure 2. Left: Stimuli for stereospecific depth perception experiments (Julesz, 1971). Right: Flow chart for computer system that records eye movements and modifies a CRT display contingent on the subject's eye movements (Loftus et al., 1975).

systems. For example, Miller, Norman, and Bregman ran their first subject in the Grammarsama psycholinguistic experiment the day after their computer was installed. Second, many of these labs were quick to develop general-purpose programs and programming languages for cognitive research at a time when other labs were writing individual programs anew for each separate experiment. Again, Harvard's Center for Cognitive Studies provided a good example. In that lab, by 1966, Forsyth's Lexigraph Interpreter had enabled 20 new computer users to run cognitive experiments using auditory and visual displays and to get their experiments working in a few weeks without acute trauma or chronic computeritis.

As a last historical comment, it is of interest to note the point at which we began formal computer education for graduate students in cognitive psychology. Such education began only a few years after cognitive psychologists began to use computers in research. It is appropriate to mention a few texts which appeared early on and which had a major impact on training researchers in cognitive psychology. In 1960, Miller, Galanter, and Pribram published *Plans and the Structure of Behavior*. This book incorporated conceptual ideas about computer functioning as theoretical constructs in psychological theories of information processing. In 1961, Holland and Skinner published *The Analysis of Behavior* which provided much of the conceptual foundation

for research in computer-aided instruction and human learning. In 1963, Bert Green wrote *Digital Computers in Research*, the first text for behavioral and social scientists on all aspects of computer usage. Also, in 1963, Feigenbaum and Feldman edited *Computers and Thought* which provided exciting examples of computer simulation in perception, memory, learning, decision making, concept formation, and problem solving. Finally, in 1967, William Uttal published *Real-Time Computers* which served as the major text for training students to use computers as the central component in the cognitive research laboratory. That brings our historical review of computers in cognitive psychology almost up to the present.

QUALITATIVE EXAMPLES OF COMPUTER USAGE IN COGNITIVE RESEARCH

We feel that computers have aided research in three different ways: (1) they have increased the ease and flexibility with which we can do research, (2) they have increased the precision and the reliability of our experiments, and (3) they have made possible various experimental procedures that were otherwise impossible or almost impossible. To illustrate these points, let us examine a few examples from each of three areas of cognitive research.

Figure 2 illustrates two ways in which computers are used in perception research. On the left is an

Figure 3. Top: Representation of computer-generated synthesized speech stimuli (Cutting, 1975). Bottom: Word-by-word reading times for computer-controlled psycholinguistics study (Aaronson & Scarborough, 1976).

example of random dot stereograms developed by Bela Julesz (1971). The computer generates these matrices according to programmed conditional probability rules such that either matrix alone appears random and two-dimensional. However, when the two are viewed together stereoscopically, a three-dimensional pattern emerges. Such matrices have provided a valuable tool to study the role of various stimulus factors in depth perception, to shed light on several theoretical issues concerning the nature of stereopsis, and to establish the relationship between pattern perception and depth perception. Recently, Julesz has produced stereograms that move dynamically, in order to study the relationships between motion and depth perception. The stereograms provide a research tool that is unique, and the generation of these stimuli involves so much computation, as well as spatial and temporal precision in the displays, that it is really not possible to produce them without a computer.

On the right of this figure is a flow chart of a computer-controlled visual display and eye-movement recording system developed by Geoffrey Loftus (1975). Prior to the use of computers, eye-movements could be recorded on film or other devices and later analyzed manually. But, these noncomputer methods of analysis are so tedious, time-consuming, and open to various types of error, that it is simply not possible to run experiments that require the collection of very much data. Further, the computer system in this figure makes it possible to alter the stimulus display on line, contingent on various aspects of the subject's eye-movement patterns. Loftus and others have already made important empirical and theoretical contributions to the study of pattern and motion

perception that would not be possible without computers.

Figure 3 illustrates two uses of computers in psycholinguistics. The top portion represents a speech spectrogram painted for use in the speech synthesizer programs of Cutting (1975) at the Haskins Laboratory in Connecticut. More recently, researchers have been producing speech by incorporating electronic speech synthesizers directly into the computer hardware (as at the Bell Laboratories), and also by using programs to edit natural tape-recorded speech; for example, to provide uniform compression or expansion, or to selectively delete vowels, peaks, particular frequencies or transients. Comparing spectrographs of real and synthesized speech has yielded theoretical insights regarding the nature of speech production.

On the bottom of this figure are some data collected from a computer-controlled subject-paced reading experiment in our laboratory (Aaronson & Scarborough, 1976). The computer recorded the word-by-word reading times for subjects reading sentences for later recall or comprehension tests. The figure shows prolonged pauses at phrase boundaries for the recall subjects but not for the comprehension subjects. The on-line real-time interaction needed between the subject, the displays, and the timer, plus the resulting volume of data would make it prohibitive to run this type of study without a computer.

Figure 4 illustrates the use of computers in some recent memory and learning experiments. The left side of this figure illustrates one of Patrick Suppes' (1968) projects. A first-grade pupil is shown two possible answers to an arithmetic problem displayed at the top of the computer oscilloscope. As he watches, verbal instructions are communicated

Figure 4. Left: A pupil solving arithmetic problems in a computer-aided instruction project (Suppes, 1968). Right: Recall times and errors for a computer-controlled serial recall task in which the nature and delay of feedback were varied (Aaronson & Grupsmith, Note 2).

through earphones and he signals his choice of answer to the computer with the machine's light pen, or he might type a number on the keyboard. This computer system makes possible individualized instruction, as the arithmetic problems are selected by branching subroutines based on the pupil's past learning performance. The large computer memory can store both a large body of curriculum material and detailed learning histories for a large number of students. Individual performance information is given to the pupil in an interactive system as immediate feedback after each problem, and statistics on both individual and class performance are computed for the teacher. On the right of this figure are some data from our own computer-based learning lab. In multi-trial serial recall tasks, subjects received two kinds of information feedback from the computer. Some subjects were shown how many letters they recalled correctly, immediately after they typed the entire list on each trial. Other subjects heard a tone that signaled accuracy information instantaneously, letter by letter, while their fingers were still typing each individual key. Such instantaneous reinforcement not only improved subsequent learning of the reinforced letters, it also changed the subject's cognitive strategy for coding the entire list. As the time and error data on this slide show, instantaneous reinforcement encouraged subjects to chunk the verbal items into subgroups. But, subjects with "normal" postlist reinforcement showed far less organized performance. A computerized teacher was absolutely necessary to analyze the subjects' errors on-line and to provide instantaneous reinforcement to improve learning in these ways.

Our discussion so far has shown that computers are involved in all phases of psychological research: (1) experimental design, enabling new types of paradigms and complex counterbalancing and

randomization of conditions, (2) generating, coordinating, sequencing, and calibrating stimulus displays for various sensory modalities, (3) collecting response data for discrete and continuous responses as well as temporal information about those responses, (4) performing data analyses from both on- and off-line experiments including descriptive trends as well as statistical tests, and finally (5) theory development in the form of simulation models, parameter estimation, and goodness-of-fit tests for algebraic models, as well as contributing conceptual ideas for information-processing theories of cognition.

QUANTITATIVE INFORMATION ON COMPUTER USAGE IN COGNITIVE RESEARCH

The examples we have considered lead us to ask some further questions about the full impact of computers on cognitive psychology. How typical are these particular examples? To what extent are computers really being used in cognitive psychology today? How does computer usage differ among the various sub-areas of cognitive psychology: perception, memory, learning, and complex thought processes? In what ways do research costs differ between computer-based and noncomputer projects? To answer these questions, we examined data on research funding from the National Institute of Mental Health (NIMH). In particular, we used the budget information from proposals funded during the past 9 years from two NIMH sections that handle many of the cognitive grants: the Personality and Cognition Section and the Experimental Psychology Section of the Behavioral Sciences Research Branch. We should be cautious about drawing generalities from the data we will see in the next few slides, as they do not include many other agencies that fund cognitive research, such as the National Science Foundation,

Figure 5. Funding trends during the past 9 years for computer-based and noncomputer cognitive research projects assigned to two NIMH review sections. (A) The number of grantees funded. (B) The mean size of individual grants. (C) The total amount of funds awarded to all grants in each category.

other programs within NIMH, and the National Institutes of Health, as well as private foundations, and direct university support.

To provide quantitative analyses of computer and noncomputer cognitive research, we used three types of data. (1) The NIMH key-word abstracts describing the research projects were used as a basis for classifying projects into cognitive and noncognitive research, and then into four sub-areas of cognition. For these analyses, our definition of cognition was restricted to research with human subjects. Two of us independently categorized these abstracts, and our agreement was high: we agreed 97% of the time in the cognitive/noncognitive sorting, and 93% of the time in classifying projects as focused primarily on perception, memory, learning, or complex thought processes.¹ We defined this last category, "thinking," to include problem solving, decision making, concept formation, and psycholinguistics. (2) We used the yearly budget sheets, along with the abstracts, in order to classify the projects as computer or noncomputer for any given year. Computer projects were identifiable by budget items such as programmers' salaries², computer hardware, supplies, service contracts, and machine time costs. We labeled as computer-based research those projects that used computers heavily for functions other than routine statistics, e.g., in generating stimuli, in controlling on-line labs, and in doing algebraic and simulation model development. (3) We used the award notices along with the budget sheets, in order to compute the amount of funds awarded for various types of research costs such as personnel or equipment.

Figure 5 compares the trends over the last 9 years for computer and noncomputer cognitive research. Panel A indicates that there has been a strong and continuing shift in the number of grantees³ doing computer and noncomputer research. The top line on the graph indicates that the total number of grantees remains roughly constant throughout, so this shift represents a true trade off. Over the past 9 years, the proportion of grantees heavily involved with computers increased from 15% to 46% of the total number of (funded) grantees. In Panel B, the average

size of an individual grant, in thousands of dollars, has been graphed. We see throughout that the typical computer-based project costs a good bit more than a noncomputer project. The cost differences narrowed somewhat between 1967 and 1973, but appear to be diverging again. An inspection of more detailed data suggests that this recent divergence might be attributed to increases in the number of computer peripherals (e.g., display terminals) and in the increased costs of service contracts, rather than to programmers' salaries or computer supplies. Panel C shows the total number of dollars (in millions) awarded to computer and noncomputer projects.⁴ There is a strong and consistent shift from noncomputer to computer funding. For this sample, over the past 9 years, the proportion of awarded dollars for computer-based research increased from 28% to 57% of the funds spent on cognitive research.

Figure 6 compares the trends in computer-based research among the four sub-areas of cognitive psychology. The Y axes for all of these graphs reflect the percentage of computer-to-total (computer plus noncomputer) data within each sub-area of cognition. There is a pair-wise split: memory and learning show similar trends, and perception and thinking appear more similar to each other. In Panel A, memory and learning start with a higher percentage of computer grantees but end with a lower percentage than perception and thinking. Memory and learning increased their computer grantees from 20% to only 30%, while perception and thinking went from 10% to 60%. Panel B shows that computer grants in memory and learning cost a good bit more than noncomputer grants. But, in perception and thinking for the past 5 years, the grant costs have been almost the same for computer and noncomputer projects; the curves are close to the 50% line. This cost difference holds on an absolute basis also: during the past 5 years, computer-based grants in memory and learning have averaged \$35,000, while noncomputer grants in those areas, as well as all grants in perception and thinking have been about \$25,000. Panel C shows the percentage of the total awarded funds in each sub-area going to computer, relative to noncomputer, research. Again, perception and thinking show the

Figure 6. A comparison of funding trends in computer-based and noncomputer research among four sub-areas of cognitive psychology: perception (P), thinking (T), memory (M), learning (L). (A) The proportion of grantees that are computer-based. (B) The ratio of the mean computer grant size to the sum of the mean computer and noncomputer grant sizes. (C) The proportion of the total funds awarded to cognitive projects that went to computer-based cognitive projects.

greatest increase over the past 9 years, while memory and learning remain somewhat more stable.

Figure 7 shows how grant funds are distributed among expense categories. We have graphed the percentage of the average grantee's budget spent for personnel, equipment, supplies, and other expenses. The category "other" on NIMH budget forms includes subject fees, equipment maintenance costs, and computer time. The four categories in Figure 7 constitute 97% of the grantee's budget. The remaining 3% were omitted from this analysis and include the costs of travel, consultants, publications, and renovations, which were all about equal among computer and noncomputer projects. The data are strikingly consistent. For all sub-areas of cognition, computer-based researchers, indicated by open bars, spend proportionately less for personnel and more for the other three categories, than their noncomputer colleagues. This graph indicates a clear man-machine trade off, which holds on an absolute as well as a relative basis. Computer-based projects spend fewer dollars on people and more dollars on machines, their supplies, and service costs. This picture is actually an underestimate of the trends, as many computer labs in our sample are also supported by university funds and by equipment grants from other agencies. These data on NIMH research funding hold an important place in any analysis of the impact of computers on cognitive psychology.

Now that computers have invaded our cognitive labs, what have we been doing with them over the past several years? To partially answer this question, we used as a data base the computer articles of *Behavior Research Methods & Instrumentation* since its inception in September, 1968. Two of us tagged the articles broadly relevant to cognitive psychology and then sorted them into five piles as to content. Again, our agreement was high, 93% for all stages of sorting combined. Figure 8 shows the results of this tabulation. The top and bottom graphs show the number and the percentage of papers in five categories. On the left, the two categories of general

systems development, hardware and software, are relevant to research in all sub-areas of cognitive psychology. For example, these papers might deal with general-purpose interface circuitry or with user-oriented programming languages. On the right are more special-purpose papers: statistical programs, theoretical papers dealing with simulation and model testing, and papers dealing with specific types of experiments in one or another sub-area of cognitive psychology. The experimental papers included both hardware and software development—for example, programs to generate random-dot stereograms or circuitry to record eye movements on line. Both the top and bottom graphs tell the same logical story about computer developments over the past several years, and the data are probably relevant to all of experimental psychology in general. In the earlier years, most of the papers involved systems developments. At first most reports concerned computer hardware, as many of us were building new computer-based labs at the end of the 60s. Once the computers were working and able to control on-line experiments, we discovered the advantages of developing general-purpose languages rather than

Figure 7. The percentage of the average grantee's budget spent for personnel (P), equipment (E), supplies (S), and other (O) costs for computer-based and for noncomputer projects in each of four sub-areas of cognitive psychology.

Figure 8. The number (top) and the percentage (bottom) of BRMI papers in each of five categories relevant to computer-based cognitive research. For each 2-year period, the percentages for all five categories combined sum to 100%, even though two categories are graphed on the left and three on the right.

writing separate programs for each individual experiment. More recently, however, cognitive psychologists have been developing statistical and theoretical programs to analyze and interpret the data directly on their laboratory computers, or over the newly installed lines connecting these labs to the large university computer centers. Recent special-purpose experimental papers frequently deal with complex methodology needing quite an array of peripheral equipment, such as eye-movement recorders or speech synthesizers.

The data reported from the two NIMH sections suggest that various governmental and private institutions have equipped a number of cognitive psychology labs with sophisticated computer hardware. The sample of articles in *BRMI* complements the funding data. They show that we have learned how to use that hardware in all phases of our research from experimental design, to on-line control, to data analyses and model building.

ADVANTAGES AND DANGERS OF COMPUTERS IN COGNITIVE RESEARCH

Dangers

So far we have focused on how computers have been used in research, with an optimistic view of their successes. For a moment, let us examine four classes of problems that have been encountered in a number of computer-based labs: money, time, systems functioning, and experimenter judgment.

Money. Although the cost of computer systems has been decreasing over the past few years because of

engineering developments and market demands, a computer lab is still a good bit more expensive than most labs with more traditional equipment. In addition to the hardware, companies are now selling, rather than giving away, their systems software. Environmental modifications for improved temperature and humidity control are often needed and are costly, and programmers' salaries must be added to research costs. Although most hardware costs are decreasing, repair and maintenance costs are rising sharply, as are the costs of interfacing stimulus display and response devices. Some labs have made a major error in purchasing a computer from a one-time-available source of funds and then not being able to support it financially.

Time. Four types of time problems are encountered. The time to learn to use the machine is generally far longer than for more traditional equipment. The time to write the initial experimental programs and user languages can be long, and often exceeds a year. Down-time is often long, and generally not under the user's control. Finally, the fact that computer labs are often shared among researchers means that available computer time may be limited.

Systems problems. When more traditional lab equipment is not working properly, we generally spot it immediately and clearly, but computer hardware and software failures often take a long time to detect. There are at least two types of systems problems that are very insidious. First, company-supplied software and/or hardware may not function in the way described by the manuals. Random-number generators may not be very random, and programmable clocks may or may not count the overflow bit when timing displays and response latencies. Statpacks and experimental programs obtained from other researchers may have all manner of undetected "bugs," and programs that run well on one machine may have different timing and reliability properties on another machine. A second class of systems problems arises from the fact that equipment failures often occur gradually, in small amounts, or at infrequent intervals, making their detection difficult. This is particularly true for analog equipment and for many peripheral I/O devices.

As psychologists, we are particularly vulnerable to these classes of problems. Somehow many of us have a religious belief in the infallibility of computer systems, but man frequently develops beliefs about things he does not fully understand! Coupled with this faith goes a negligence in checking and calibrating systems at frequent intervals, as we would do with more standard lab equipment.

Experimenter judgment. A computer is quite capable of leading users astray from doing high-quality psychology research. In some cases, the psychologist becomes intrigued with the intellectual

capabilities of his machine and spends hundreds of hours designing programs that are far more elegant, sophisticated, and flexible than his research will ever require. In the process, these psychologists become newly converted programmers instead. There is a second way the psychologist's judgment all too often fails. Once set into action, the computer is quite capable of running at least twice as many experiments, twice as fast, as the psychologist could do alone. Thus, the computer misleads the researcher into defining productivity in terms of number of experiments run, rather than number of good ideas about important theoretical issues in cognitive psychology.

Advantages

Computers improve our research capabilities significantly over the more traditional laboratory configurations.

Precision and reliability of experiments. The use of computers has increased precision and decreased variability in several ways: (1) Equipment variability is reduced far below that for slide projectors, memory drums, and cam timers. The resolution of computer (crystal) clocks and the time to activate solid state switches or to execute an instruction are generally a few microseconds, and the reliability is one or more orders of magnitude better than this. (2) Because the experimenter and his differential social interactions can be removed, a fully automated laboratory allows reductions in between-subject variability. (3) Subject-paced trials, immediate feedback, and active on-line participation help raise the motivational level and consequently decrease within-subject variance. Further, within a session, a smooth-running automated system often permits a 50% larger data sample than does standard equipment. (4) Finally, variability due to experimenter errors, e.g., in setting knobs and recording data, are eliminated.

Ease and flexibility of doing research. Flexibility in experimental design occurs because event sequencing (e.g., feedback and stimulus ordering) and stimulus attributes (e.g., quantity, duration, intensity) can easily be varied under program control or can be made contingent on the subject's response and latencies. This flexibility allows rapid pilot work to determine the optimal experimental conditions and permits easy parametric variation within and between studies.

Research capabilities not possible without the use of computers. New types of stimulus displays can now be generated, as illustrated by Julesz's stereograms and Cutting's synthetic speech. New types of experimental paradigms are possible, as illustrated by Suppes', and by our own, real-time interactive learning labs. We can now collect and analyze larger quantities of response data, and this quantitative difference is of such a magnitude that it has made a

qualitative difference in the types of research designs used, as illustrated by Loftus' work with eye-movement data, and Aaronson and Scarborough's work with reading times. Finally, and most important, the computer as a research tool, has enabled us to reveal some new psychological phenomena that were not previously obvious, as illustrated by Sperling's (1971) demonstration that people can scan information into memory at rates as high as 125 items/sec and by Julesz's demonstration that people are capable of experiencing stereoscopic depth perception prior to the existence of monocular pattern perception.

Our conclusion is that the impact of computers on cognitive psychology has been very rapid and very strong. Computers have had a significant impact on research in cognitive psychology: They have increased the ease and the flexibility with which we can do research; they have increased the precision and the reliability of our experiments; and they have made possible various experimental procedures that were previously impossible. A most important question, however, is whether or not computers will markedly increase the rate at which we observe new psychological phenomena, the rate at which we acquire new information about mental processes, and the rate at which we gain a theoretical understanding of how those cognitive processes are performed by the human being. Perhaps, by the year 2,000, at the 31st Annual Meeting of our On-Line Computer Conference in Psychology, we will have a partial answer to this question.

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NOTES

1. Only regular research proposals were included in our sample; programmatic proposals and small grants were excluded from our analyses.
2. Salary information was available in terms of positions or functions of grant personnel, but individual identifying information was deleted from the budget sheets available to us to protect the privacy of the investigators.
3. We are using the term "grantee" to denote the individual principal investigator responsible for the scientific research of an awarded grant. This differs from the technical terminology at NIMH, where "grantee" denotes the sponsoring institution, e.g., the university at which a funded investigator is employed.
4. The data in Panel C are pooled (summed) over all grantees, regardless of area within cognitive psychology. The data in Panel B are arithmetic averages over the four sub-areas in cognition, with each sub-area weighted equally (not weighted by sample size). Hence, the data in Panel C are not the simple product of Panels A and B (which would be the case if the Panel B data were weighted rather than arithmetic means).