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BEYOND BABBAGE*

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Charles Babbage, mathematician and general scientist, published in 1822 a paper entitled "Observations on the application of machinery to the computation of mathematical tables." Here, Babbage describes his Difference Engine, a machine "for constructing tables which have no order of differences constant. A vast variety of equations of finite differences may by its means be solved, and a variety of tables ··· could be calculated ··· with (little) exertion of human thought. Another and very remarkable point in the structure of this machine is, that it will calculate tables governed by laws which have not been hitherto shown to be explicitly determinable, or that it will solve equations for which analytical methods of solution have not yet been contrived" ([44], p. 299). Alert to the possibility of errors made by "persons employed to copy the figures presented by the engines," he also contrived means by which the machine would compose type and print answers from its computations.

Babbage's proposal was well received in London. Over a period of years, he received a sum of 17,000 pounds from the British Government, and, with a like sum from his private fortune, he proceeded toward the development of his machine. Babbage's ideas for improving design outstripped engineering progress, however, and frequent revision of the project prevented its successful completion. By 1834, Babbage was intent upon developing a much more general-purpose machine, his Analytical Engine—a card-controlled device which was described in 1842 by the Countess of Lovelace in the following terms. "··· the Analytical Engine does not occupy common ground with mere 'calculating machines.' It holds a position wholly its own; and the considerations it suggests are most interesting in their nature. In enabling mechanism to combine together *general* symbols in successions of unlimited variety and extent, a uniting link is established between the operations of matter and the abstract mental processes ···" ([44], p. 252). Is it not re-

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markable that, 130 years ago, a digital computer was designed which incorporated distinctions between Number Cards, "to communicate the constants of a problem to the machine," Directive Cards, "to direct to which particular place in the engine these numbers, or any intermediate numbers arising in the course of calculation, are to be conveyed," and Operation Cards, "to direct the actual operations to be performed" ([44], p. 332).

A. M. Turing, discussing digital computers more than a century later, remarked that "Babbage had all the essential ideas," but that due to its slow speed (although "definitely faster than a human computer") and due to the purely mechanical storage facility, Babbage's machine "at that time was not such a very attractive prospect" [76]. With electronics having largely replaced mechanics as appropriate bases for machine construction, the technology of this century has been prepared to translate machine concepts into concrete form, and indeed promptly to improve upon them. Witness the dramatic developments of the past decade.

During recent years, there also are signs of considerable acceleration of efforts towards promoting the development of psychology as a quantitative science, with more frequent publication of books and journal articles devoted to quantitative psychology, as well as new and expanding programs of training and research. Undoubtedly, computer advances and progress in quantitative psychology share some common determinants, if only in the common Zeitgeist which fosters both developments. In any case, it is clear that computer systems serve now and in the future to extend almost indefinitely the horizons of psychometric research.

While few would quarrel with this prediction, the full extent of the potential influence of computers upon psychometric research may not be generally recognized. The survey of computer usage in psychology departments reported by Vandenberg, Green, and Wrigley [77] suggests that relatively few psychologists are directly familiar with computers, and that computer use by psychologists is largely restricted to data analysis. Only few laboratories of psychology as yet have direct access to and control of data processing equipment. As small computers become available within psychological laboratories, or as central large-computer facilities develop the capacity for parallel processing, with consoles available to individual psychologists, the range of computer applications in psychology certainly will expand. I wish to discuss some of these applications, emphasizing their relevance to the aims of the Psychometric Society.

Parenthetically we may note that the membership of the Psychometric Society includes many who have been actively promoting new developments in quantitative or mathematical psychology as well as in computer work. As a Society, it seems appropriate to recognize the substantial advances which have been made and to plan a broadened scientific program which more amply accommodates them.

Data Processing

Quite explicit in the design of digital computers is the principle that all arithmetic may be reduced to counting, and that, using numerical analysis, much of mathematics can be reduced to arithmetic. With rate of counting measured in millionths or even billionths of a second, the cost of executing complex quantitative analyses of data, once an appropriate computer program is available, is a cost measured simply in seconds of computer time. Implications are obvious to us all. Where, a decade ago, several man months were required to perform a moderate-sized factor analysis, the same analysis may be performed today in minutes. Where, a few years ago, multivariate analysis of variance and multiple discriminant function analysis were only of theoretical interest, today computations needed for such analyses are readily performed, even with large numbers of dependent variates and nonorthogonal designs.

Recognizing the danger that investigators are easily tempted to use available programs, even though inappropriate to their needs, it is proper to stress continually the responsibility of psychologists to exercise care in design of their studies and to develop mastery of the methods which they select for data analysis. Indeed, the availability of machines which so dramatically extend the range of models for data analysis creates need for new and better training programs for the understanding and use of those models. Those of us engaged in the training of quantitative psychologists must be alert to this need, and should also be certain that our students master the principles of computer programming, enabling them to make better use of these powerful tools for data analysis.

The time and effort required to write programs for general multivariate procedures and other complex methods of data analysis are far from trivial. Hopefully, as truly common machine languages are more widely adopted, developments at one site may more readily be communicated and directly utilized at another. At present, the practical incompatibility of programs prepared on one machine for operation on another machine remains a major hindrance. Further inefficiencies result from failures in human communication. Too often we hear of the belated discovery that even at the same institution, utilizing the same computation center, independent groups of investigators are unaware that they simultaneously are working toward common data processing goals. Some duplication of programming effort clearly is unavoidable. And some is even beneficial. But costly and unnecessary replication of programming systems will be reduced with better communication and adoption of common machine languages for scientific data analysis.

Other programming efficiencies also may be recognized. Often practical considerations, most frequently the pressure of time, dictate need for special purpose programs to be prepared for specific problems of data analysis. Programmers at a given institution may be almost exclusively engaged in these enterprises. A consequent risk is the development of a program library which becomes a hodge-podge of miscellaneous routines, each of which served the specific purpose of some one user at one time, but which only by good fortune is found adequate for a wider range of problems. In contrast, it is possible to develop a coordinated system of subroutines designed for general purpose use within a given problem domain (e.g., Bock [5], Healy [27], Horst, Dvorak, and Wright [28], Smith, Gnanadesikan, and Hughes [65], Tryon [32, pp. 195–199; 73]). Specific problems are identified by a set of parameters indicating the special features of the solution required.

An example of this approach is provided by the matrix compiler developed at the University of North Carolina by Darrell Bock. Each subroutine within the system represents a single matrix operation—addition, subtraction, multiplication, inversion, transposition, extraction of diagonal entries, read-in, print-out, etc. Each requires as parameters the order of matrices and the memory location of their initial elements. Special routines are available for operations on symmetric matrices, typically stored only in their lower triangular forms. Programs for a wide range of analyses may be prepared using this system, each program consisting essentially of a list of matrix equations. General univariate and multivariate analysis of variance is accommodated as are multivariate stepwise regression analysis, canonical correlation analysis, factor analysis, psychometric scaling analysis, and analysis of data in contingency tables. Recently this system of matrix operations, originally designed for the Univac 1105, has been translated and programmed for the LGP-30 at the Psychometric Laboratory in Chapel Hill. Here it is arranged so that the operator may exercise manual control at the Flexowriter keyboard. The resultant machine resembles a desk calculator for matrix operations. With data matrices prepared on perforated paper tape, the operator may input such matrices, invert one, transpose a second, determine their product, store and print the result, each step being executed by depressing a few Flexowriter keys in accordance with a mnemonic code of commands. Prepared for a computer which is readily available to graduate students and staff, this system is proving to be highly convenient.

Data processing by computer is not limited to analysis of quantitative data, since a bit pattern may represent any symbol, numerical or not. One class of problems which has received much attention is that of analyzing natural language data. For English language data, among the simpler uses which computers have served are the determination of word counts in large bodies of text in an effort to resolve an authorship dispute [45], the computation of transition frequencies between pairs of word classes in speech from aphasic and normal speakers [19], the processing of speech from aphasic and normal speakers to determine functional regularities between frequency of word occurrence and rank popularity of the word [54], and grammatical classification of words on the basis of dictionary look-up procedures [e.g., 31].

Somewhat greater sophistication is achieved in grammatical coding by dictionary look-up procedures combined with devices to resolve ambiguities by decisions based upon contextual features [e.g., 35].

A great deal of computer work on language has been oriented toward translation from one natural language to another [e.g., 13, 14, 53, 85]. A number of investigators have developed programs for the analysis of syntactic structure [e.g., 23, 26, 64]. Similar to the problems of linguistic analysis are those of storage and retrieval of texts including literature search, abstracting, and indexing [4, 10, 33, 34, 52, 70, 78], and problems of content analysis of texts retrieved [68]. Many applications share with these the need to make classificatory decisions or diagnoses. Considerable success has been achieved by computer programs designed for optimal classification in vocational selection [e.g., 28], clinical psychology or psychiatry [e.g., 3, 36, 55, 56], and neurology [e.g., 81].

The greatest single challenge presented by advances in data processing is closely linked with the problem of communication between man and machine, mentioned earlier. With increasing frequency, reports of research depend upon data analysis carried out by computer programs. Evaluation of such reports logically demands evaluation of those computer programs. Today, programs with similar purposes but prepared at different installations, by programmers with a wide range of qualifications, will themselves exhibit variable adequacy. But if they are not expressed in a problem-oriented language convenient to the human reader, their critical evaluation becomes almost impossible. In order to reinstate full scientific communication of research results, it thus is essential that we adopt a commonly understood language for specifying our data processing programs. Hopefully, a solution is not too distant, perhaps a combination of best features from ALGOL and FORTRAN. If generally adopted, such a language might allow recovery of a value from the good old days, when methods of analysis properly were subjected to the same critical scrutiny as research design and as interpretation of findings.

The Computer as a Model

Many years ago I was "enlisted" in a course on the fundamentals of radio circuitry. As an examination, at the end of one unit of training, students were assigned a performance task, that of working in front of the class to "trouble-shoot" the disorder in a radio circuit. A working model of the circuit was presented on a plywood board, perhaps 5 $\times$ 9 feet in size; the chief components, transformers, tubes, condensers, resistors, were visible at locations here and there on the surface of the display. Wiring was represented by painted black pathways on the board, connecting the components. By manipulating switches behind the board, unseen by the viewer, the instructor was able to create any of a large number of symptoms of defective radio operation.

I distinctly remember my turn on the trouble-shooting test. Using a voltmeter and two probe leads, I first took several readings. My pleasure was genuine and intense when, by happy accident, I discovered the difficulty. Placing voltmeter on the table, I turned half towards the class and proudly announced, "There is a break in the circuit." Then, placing the index finger of my left hand at the terminus of one "wire," I continued, "It is located between here and here." As my right hand touched the second location, I was propelled violently backward and floorward. The consequence of closing the circuit forcefully verified my diagnosis; but the class, lost in merriment, showed no awareness of that success. From that moment, I have recognized certain economies associated with vicarious experience through abstract models as compared to painful, direct experience with the reality modeled.

The radio circuit display falls near one end of a continuum of models—a continuum from the phenomenon itself to a completely abstract representation of it. I was misled by the artistic features of the display to believe that that model was farther removed from reality, and was rather shocked to discover my error.

Harman defines simulation as "the act of representing some aspects of the real world by numbers or other symbols that can be easily manipulated," and he comments, "In this sense, simulation is one of the oldest analytical tools" ([25], p. 2). Since an outstanding feature of computers is the ease of symbol manipulation, it is not surprising that we turn to them with hope for enrichened simulation models. We may distinguish two broad classes of simulation models—those dependent upon numerical analysis and a class of nonquantitative information processing models. The first class perhaps more naturally fits the interests of the Psychometric Society. Mathematical models of behavior, prior to the availability of computers, were limited by the tools available for expression and analysis of the model—the most notable tool being pencil and paper. Thus, the models proposed tended towards relatively simple form, in order that it be feasible to evaluate them. Using the computer as a device for numerical analysis, the investigator now is free, with no loss of precision, to develop richer models capable of representing theories of much greater complexity.

The first use of computers for the exploration of mathematical models of human behavior seems to be that of Bush and Mosteller [8], who adopted Monte Carlo procedures for the statistical evaluation of their two-operator linear learning model. Bush and Mosteller also performed Monte Carlo experiments to compare a variety of competing learning models [9]. Gorn [20] presents a more extensive discussion of computer simulation using probability models of learning. The value of computer analysis is apparent also in the studies of Markov learning models reported by Suppes and Atkinson [69]. Statistical simulation by Monte Carlo techniques offers effective predictive models in a variety of applied areas (see [15]). Adams and Webber [2] illustrate application of a Monte Carlo model of human tracking performance with encouraging results. Promising work also has been recently reported of simulation of inductive inference, utilizing principles of Bayesian statistics [82, 84].

One recently proposed computer model deserves special attention, that of Roger Shepard [59, 60]. Shepard's computer program represents a model of multidimensional scaling or, alternatively, may be considered a method for nonmetric factor analysis. Given data which represent nonmetric information concerning perceived similarity of stimuli, this program aims at constructing a metric configuration of those stimuli in n-dimensional Euclidean space. The program selects the smallest value of n consistent with a Euclidean model. The program assumes only that a monotonic function relates judgments of stimulus similarity and metric interstimulus distance. The program has been used with considerable success on a variety of problems. It is worthy of note that Shepard's program not only performs the iterative analysis to solve for interpoint distances. It also determines a polynomial function relating a measure of judged stimulus similarity to distance between stimuli in Euclidean space. It performs statistical tests of the adequacy of this function, presents tables summarizing the analysis, and plots on microfilm very handsome graphs displaying the fit of the model to the data.

Despite these and other illustrations of use of computers for developing and evaluating quantitative models of behavior, it seems safe to say that, in general, psychologists have been slow to adopt computers for these purposes. Chief reasons for this are not hard to find. While for data processing, the user need not be intimately associated with a computer, the same cannot be said for model building. By the nature of the enterprise, the investigator profits from working closely with the computer, programming, testing, and modifying his model. He is not merely a machine user who may hand data to an intermediary for analysis by a standard program. Until psychologists have greater direct access to machines, and are willing to make greater investments of effort toward mastering programming principles, they will probably fail to appreciate the full potential of computers in connection with quantitative models.

While quantitative models make use of computers for the power of numerical analysis, information processing models capitalize upon the general capacities of computers to manipulate symbols which may stand for nonnumerical concepts. An information processing theory may be fully as rigorous as quantitative theory. It utilizes a formal language with explicit constraints, and in this respect resembles conventional mathematics. Precision and clarity may be no less than in computation. We may classify information processing models as a branch of mathematical logic, in which case they are structurally parallel to quantitative models.

The potential for studying correspondence between artificial and natural information processing systems was recognized early by mathematicians who pioneered the development of computers, notably by Turing [75, 76] and von Neumann [79, 80], and, as we have seen, appears to have been suggested by Babbage. Certainly it was acknowledged in 1887 by Charles Sanders Peirce, who wrote in Volume I of the *American Journal of Psychology*, "Precisely how much of the business of thinking a machine could possibly be made to perform, and what part of it must be left for the living mind, is a question not without conceivable practical importance; the study of it can at any rate not fail to throw needed light on the nature of the reasoning process" ([57], p. 165). In this paper, so many decades before its time, Peirce includes a discussion of the degree to which originality or initiative could characterize a "reasoning machine," and notes the single-purposed limitation of machines as compared with the less limited capacity of "the mind working with a pencil and plenty of paper" day after day. (His treatment of the power of the parenthesis as a symbol for adding proposition to proposition also appears to belong to the 1950's rather than the 1880's.) Peirce, who so greatly affected the course of psychology and education via his influence on William James and John Dewey, who rightly may be considered if not the father then the grandfather of logical positivism, here further surprises us by analyzing two existing crank-driven instruments of logic in terms of the evidence they afford concerning the human reasoning process.

In 1946, Boring recommended that the psychological properties of the human organism could profitably be considered by thinking of the person as a machine; Boring noted that "It is a procedure that keeps us clear" ([6], p. 177). Today, 18 years after Boring's paper "Mind and Mechanism," and 76 years after Peirce's note on "Logical Machines," it is increasingly recognized that much of the value of the information processing approach is the conceptual clarity which results when computer subroutines are offered as analogies to psychological processing units. A major benefit accrues when the investigator can exploit the capacity of the computer to expose slipshod thinking, incomplete conceptualization, and confused portrayals which may escape detection in a verbally expressed theory. Yet, other prominent advantages appear after a model has been prepared as a working computer program. On the one hand, if the program runs successfully, the model has passed a test of the adequacy of its description. And most important, consequences of the model which have not been recognized due to the complexity of the system may be discovered through simulated operations.

The first explicit attempt to program on a computer an information processing theory of human behavior is that of Newell and Simon in 1956, the Logic Theorist [49]. (See also Newell, Shaw, and Simon [48].) A less restrictive theory is represented by the General Problem Solver (Newell, Shaw, and Simon [47]). The documentation of IPL-V [46], the list processing language introduced by Newell and his associates, has stimulated further attention to computer models of human behavior which are discussed with increasing frequency in recent psychological literature (e.g., Borko [7], Feigenbaum and Simon [17], Feldman [18], Green [22], Guilford [24], Hunt [29], Laughery and Gregg [37], Miller [41], Miller, Galanter, and Pribram [42], Newell and Simon [50], Tomkins and Messick [72]). An excellent statement concerning the status of heuristic programs available as of 1960 is provided by Minsky [43].

The amount of attention already devoted towards developing computer models of cognitive processes is suggested by the scope of the bibliographic surveys recently provided by Simmons and Simmons [62, 63]. Their citations of the literature exclude information retrieval studies, papers on language translation, and papers devoted to engineering aspects of artificial intelligence. Restricting attention to simulation of cognitive processes, they annotate 958 papers available as of Spring, 1961. More than half of these appeared in 1959 or later. A projection of these data beyond 1961 leads to a conservative expectation of more than 1500 papers on this topic to the present date!

A comment is in order concerning the character of projects collected under the topic "Simulation of cognitive processes." Quite typically, investigators begin by taking account of principles at least superficially resembling psychological processes. But in the course of model-building, the temptation may be very great to shift gears, so to speak, and adopt criteria of logical consistency and adaptive performance in preference to criteria concerning the matching of processes in the model to human cognitive processes. Resulting programs may perform human-like tasks but not necessarily in human-like fashion. This temptation to switch goals from simulation of behavior to optimal task accomplishment can be resisted, as demonstrated by some investigators, notably Abelson [1], Colby [11], Feldman [18], and Johnson [30].

Computer models of human functioning have tended to fall into one of two classes. Either they are normative models without necessary descriptive power for any one human subject, or they are highly deterministic models designed to describe and predict a segment of behavior for *only* one particular individual. The work of Edward Johnson [30] is of interest in that it falls in neither of these classes. Johnson performed a detailed analysis of data from 11 subjects in their attempts to solve a variety of concept-formation problems. A number of principles or strategies were identified, many common to the attempts of several subjects. A model was developed from these principles, with the feature that, by pre-setting certain individual difference parameters, its "style" of problem solution would resemble that of one or another of the subjects. The solutions to a set of problems as provided by the model were found to be essentially indistinguishable from those of the target subject for the corresponding problems. This seems a particular promising task—establishing a general model for some component of behavior and allowing for individual differences by varying the parameters.

Great strides have been made recently in one field related to simulation, the field of pattern recognition [e.g., 7, 21, 22]. Work in both visual form perception and auditory pattern perception by computer has met with considerable success. Not all these attempts have begun by considering the nature of processes used by humans in recognizing form. Indeed, some have frankly hoped to improve upon them. Apart from its value to the psychology of perception, this work promises to extend the power of the computer as a scientific tool. On the visual side, for example, a computer capable of reading data printed in a natural language offers conveniences not available from computers dependent upon punched card input. The prospect of speech recognition suggests still greater vistas.

In information processing machines and pattern recognition systems in particular, the value of the system depends upon its capacity to generalize. The logic of a successful generalizing machine seems to be precisely the inductive logic of the scientific method [39]. A pattern of signals is introduced to the observer (or machine). The observer generalizes in the form of an hypothesis specifying the expected resultant pattern if act A is performed. After performing act A, the observer records the pattern of signals following the act and compares it with the hypothesized pattern. If a discrepancy is found, the observer adjusts the hypothesis and retests. The precision, speed, tolerance for complexity, and conceptual neutrality of a computer system suggest ultimate contributions to the development of theory as well as the presently realizable value for data analysis and detection of theoretical weaknesses. It is instructive to compare the logic of a generalizing machine with a definition of the aim of psychometrics given by Ledyard Tucker in his presidential address before this Society in 1955, "to maximize the extent to which observations of psychological phenomena can be validly matched with expectations obtained from rational theories" ([74], p. 268). By "expectations" Tucker meant "definite statements." In discussing how to achieve this aim, Tucker sharply distinguished vagueness from generality, a distinction which computer models definitely can help to maintain.

Information processing models differ from statistical models of human behavior in several respects. One of these is in the number of points of contact with empirical data. The information processing approach aims not only at predictive correspondence of gross performance measures, but also at isomorphism of model and subject at a number of intermediate points between presentation of a stimulus and elicitation of response. With such ambitious aims, this approach challenges the psychologist to hypothesize mechanisms by which the human organism processes symbols in learning, problem solving, concept formation, etc., so that these mechanisms may be programmed into the model. It offers a further challenge, at the level of evaluation and measurement, to develop appropriate criteria for credibility of the model in its dynamic representation—the output of the computer program—at the various points of contact with the human subject.

Problems of man-machine communication seem even more severe in the area of simulation than in data processing. Consider the difficulties faced by the investigator who has successfully embedded his cognitive theory in a computer program, and then desires to communicate the nature of the theory. A verbal description would be lengthy, yet incomplete. Flow diagrams may be helpful for presenting the general form of a program. But with large and complex programs, either they are at a level too gross to be very helpful or they are almost as detailed as the complete coding record. That record is essentially illegible to the audience, most of whom have not mastered the language in which coding was performed. For those who have, it remains difficult reading, and at best is only a static representation of the model, another important part of which demands computer operation.

Some alleviation may derive from new information processing languages more mnemonic, closer, perhaps, to natural languages, than those now available. But intrinsically, information processing models are complex. Their communication remains a problem to the investigator and to his audience. Until its solution, critics may properly question the value of a theory which is said to exist in a computer but is not subject to being grasped by the human mind, not able to influence thought about the modeled phenomena. Especially in this day of rapid technological advancement, machine-to-man and man-to-man scientific communication is a primary responsibility of investigators who would contribute to knowledge.

Computer-Controlled Experimentation

The best-known uses of computers in psychology are those involving statistical analysis of data or simulation. Indications that the computer may play an important role as an apparatus in the laboratory of experimental psychology have come from Green [21], Newman [51], White [83], and others, who emphasize the use of computers for the production of perceptual displays. The value of a computer in programmed teaching also has been recognized [e.g., 12, 40, 61]. Less generally recognized is the great potential of computers as means for control of experiments and recording of data (although a few attempts of these sorts have been discussed in the literature [e.g., 38, 66, 67, 71]).

Recently, the LGP-30 computer at the Psychometric Laboratory has been employed in several studies of human decision-making. Our approach is in apparent contrast with the suggestion of Yntema and Torgerson [87] that computer decision-making may become more efficient than that of man. Yet, in fact, such research into decision-making processes complements that view since the development of descriptive models of human decisions may enhance the design of computer programs capable of making complex decisions with greater speed and no more errors than in the human effort. One experiment along these lines is reported by Yntema and Klem [86], who constructed a computer program to make decisions consistent with ratings by human judges of the variables important to such decisions. Correspondence between decisions of the computer and the judges was good.

In the studies at the Psychometric Laboratory the essential task for subjects is the estimation of an unknown population proportion, given only partial information about its value. Subjects are presented with a small sample of observations, and also are able to profit from prolonged experience with the same parametric distribution of population proportions. Each sample is drawn by the computer and printed for the subject; the computer requests responses at appropriate times, and the subject responds by typing his estimates on the keyboard of an on-line Flexowriter. The computer supplies information about trial-to-trial results of his performance, and conveys a cumulative record of his winnings to the subject.

In one such study Rapoport [58] studied models for decision-making in a nonstationary environment. Unknown to the subject, the computer changed experimental conditions by alteration of parameters of the population distribution of proportions during certain blocks of trials. The computer program not only controlled the experiment, but also evaluated competing models of learning which predicted changes in decision strategy both within one experimental condition and between conditions. In a more recent study, Albert Amon and David Messick have studied predecisional information seeking, allowing subjects to sample sequentially at a fixed cost per observation, but able to make the required decision, i.e., to estimate the population proportion, at any point rather than having to call for another observation. Chief interest resides in the number of observations taken prior to a decision, and the relation of this to other evidence regarding the risk-taking propensities of the subject.

The use of a computer to control such experiments is found to have a number of advantages which have stimulated our enthusiasm. Standardization of experimental conditions is assured, as is precision of stimulus presentation and recording of response. The apparatus is highly flexible if general programs are prepared, allowing parameters to be varied to alter features of the experimental task. The computer is uniquely qualified for experimental designs where changes in stimulus conditions are contingent upon the course of subjects' responses; for data may be analyzed cumulatively as the subject responds, and the computer programmed to alter conditions depending upon a pre-established criterion function of the data up to trial n.

A striking advantage is related to attitude of subjects toward the experiment when it is computer controlled as contrasted with conventional experimenter-controlled tasks. Greater stability of performance levels has been found within subjects, and individual differences also are less marked. Subjects display great interest in the task, often requesting that they might return at a later date to participate further. Informal interview of subjects suggests little of the suspicious, skeptical attitude which frequently is in evidence when subjects consider an experiment a game against the experimenter.

One feature of computer-controlled experimentation could become disadvantageous. As laboratories become more automated, the human investigator may become farther and farther removed from the subject of investigation, consequently losing all opportunity to "happen upon" hypotheses from personal observation of the incidental features of an experiment. The better the investigator, the less will be this risk, for both direct observation and more detailed auditory and visual recording can be incorporated even in a fully automated laboratory.

The chief drawback of computers used to control psychological experiments is their relatively high cost. A related disadvantage is the inefficiency of using high-speed digital equipment in real-time interaction with a human subject. However, more flexible components of laboratory computer equipment now are becoming available, which provide multiple channels of input and output and allow the performance of numerous subjects to be under simultaneous study. But capital cost of such equipment, while it may decrease somewhat, is likely to remain large. Nevertheless, well before 1970, it should be anticipated that many experimental psychology laboratories will be equipped with computerized experimental apparatus. Due to their high cost, such laboratories, like those which have been established in physical and biological sciences, will require greater assurance of continuity of support, as must be recognized by university administrators and research granting agencies.

General Comments

I have tried to emphasize the importance of computers in the development of psychology as a rational quantitative science. Within psychology, members of the Psychometric Society generally are well qualified to assume leadership in the introduction of computer activities. Certainly, it is crucial that our graduate students become trained in computer use, and during their training the more intimate their contact with computers the more probably they will display wisdom in adapting computer equipment in future research.

It is likely that we are nearing the threshold of a third generation of computers, which will offer features generally not available today. Prominent engineering advances include semiconductor networks, thin-film integrated circuitry, and more compact, less costly immediate access memory. The capacity for parallel processing of multiple channels of input and many other features will soon provide the user with a choice of flexible equipment to suit his particular needs. Cost may be substantially reduced. With these anticipated advances, it will become more feasible and even more advantageous than now for psychological laboratories to acquire computer equipment.

Recognition of the profound importance of computer systems to psychology has been pioneered by Babbage, Peirce, Turing, von Neumann, Simon, none of whom are primarily identified as psychologists. There is no longer any question but that the computer is a most powerful tool for the psychologist. The only question is whether we will choose to make the best use of it or whether we will unwittingly abdicate to other disciplines the study of intelligent behavior.

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