The Psychology of Human-Computer Interaction

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Preface

Designing interactive computer systems to be efficient and easy to use is important so that people in our society may realize the potential benefits of computer-based tools. Our purpose in this book is to help lay a scientific foundation for an applied psychology concerned with the human users of interactive computer systems. Although modern cognitive psychology contains a wealth of knowledge of human behavior, it is not a simple matter to bring this knowledge to bear on the practical problems of design—to build an applied psychology that includes theory, data, and methodology.

This book is our attempt to span the gap between science and application. We have tackled a small piece of the general problem. With respect to computer science, we have focused on the task domain of text-editing and similar types of highly interactive systems. With respect to psychology, we have focused on the notion of the expert user's cognitive skill in interacting with the system, especially the temporal aspects of the interaction. We have constructed an empirically-based cognitive theory of skilled human-computer interaction in this domain. This theory is our keystone for linking science and application. On one side, we have shown that the theory is a consistent extension of the science of human information-processing. On the other side, we have simplified the theory into practical engineering models, which are the tools for designers to apply the theory. Thus, in addition to putting forth specific psychological models in this book, we have tried to make clear the general framework of an applied psychology, in which these models are but prototypical examples.

THE AUDIENCE FOR THIS BOOK

Interest in the topic of human-computer interaction is shared by people from a range of disciplines. We believe this book makes contact with the specific interests of all of these disciplines. For instance:

(1) Cognitive psychologists will find that theory and empirical methods can be extended to the analysis of a real-world domain and that a practical problem can be a fruitful vehicle for developing basic psychology.
(2) Computer scientists will find that the problem of matching computer power with user abilities may be approached using the theory and methods of the cognitive sciences.
(3) System designers will find that we have derived a number of models and principles of user performance that may be used in design.
(4) Human factors specialists, ergonomists, and human engineers will find that we have synthesized ideas from modern cognitive psychology and artificial intelligence with the old methods of task analysis and brought them to bear on the human-computer interface—which is rapidly becoming the most important domain in human factors practice.
(5) Engineers in several fields concerned with man-machine systems will find that we have extended the notion of work analysis by showing how techniques from cognitive science can be applied to the analysis of procedures that are predominantly mental.

We have used the book as the primary reference in a graduate course on "Applying Cognitive Psychology to Computer Systems," taught (by TM and SC) in the Departments of Psychology and Computer Science at Stanford University (Moran and Card, 1982). Parts of the book, in manuscript, have proven useful to others in teaching similar courses in psychology, computer science, and industrial engineering. The book would be suitable for a variety of courses: (1) a course on human factors in computer systems within a computer science department; (2) a course on human-computer interface design within a computer science department; (3) a course on the psychology of computer users within a psychology department; (4) a course on human-computer interaction within an industrial engineering or human factors department; (5) an advanced research seminar in either computer science, psychology, or industrial engineering; or (6) in a focused short course for industrial professionals. For courses with a design focus, Chapters 1 and 2 can be used to provide psychological background; and Chapters 3, 5, 7, 8, 9, and 12 can be used for analytical and practical content. For courses stressing psychological issues, Chapters 1, 2, 5, 7, 8, 10, and 11 can be used to develop basic concepts and theory.

HISTORY OF THIS RESEARCH

In 1970, Xerox established a new major research center in Palo Alto with the express purpose of exploring digital electronic technologies in support of Xerox's general concern with office information systems. Since that time, the Palo Alto Research Center (PARC) has become well known for its developments in interactive computing, based on personal computers with integral high quality graphic displays (the Alto being the first such computer), connected by a high capacity local network (the Ethernet). It has become known, as well, for being the first living embodiment of this new computational style.

From the start (early 1971) there were discussions between George Pake (then head of PARC), Robert Taylor (now manager of the Computer Sciences Laboratory of PARC), and one of us (AN, as a consultant to PARC) about the possibilities of an active role for psychological research into human interaction with computers. PARC seemed like the perfect place to attempt such an effort. Modern cognitive psychology had come a long way in understanding man as a processor of information, a view that meshed completely with the developments in computer science and artificial intelligence—indeed, derived from them in a number of particulars. The impact of the psychological advances on the human factors of how computers were used was not yet very great, though the potential was clearly there. PARC itself, being both an industrial laboratory with the concomitant underlying emphasis on application and a group engaged in basic research in computer science and artificial intelligence, provided exactly the right environment.

In 1974, opportunity became reality through Jerome Elkind (who had joined PARC to become manager of the Computer Sciences Laboratory). Two of us (TM and SC) joined PARC, and a small unit, called the *Applied Information-Processing Psychology Project* (AIP), was formed. Its charter was to create an applied psychology of human-computer interaction by conducting requisite basic research within a context of application. It was initially located within the Systems Sciences Laboratory, a sister laboratory to the Computer Sciences Laboratory, under William English, who was in charge of a group constructing an experimental interactive office-information system. One reason for its location was the early decision to concentrate on immediate, real-time human-computer interaction, especially as embodied in the use of text-editing systems, rather than on the activities of programming computers. The AIP group has remained intact through many local reorganizations and is presently a part of the Cognitive and Instructional Sciences Group.

The present book, then, presents the results of some of the main strands of the AIP group's research. The group has throughout consisted of just the three of us, in equal collaboration (SC and TM at PARC, with AN as a consultant), supported by research assistants, students, and colleagues in PARC and elsewhere.

ACKNOWLEDGEMENTS

As should be evident from the remarks above, we owe an immense debt to the PARC environment. A few of the people who played a key role in the creation of PARC were mentioned above. It is not possible to enumerate all the individuals who have played a definite role in making our tiny research group viable over the years. We would, however, like to acknowledge a few, both inside and outside of PARC. Harold Hall, Manager of the PARC Science Center, provided support for our studies in his several managerial capacities (the analysis in Chapter 9 is the result of a question he posed to us). Bert Sutherland, as Manager of the Systems Sciences Laboratory, played an important role in supporting us and allowing us the resources to pursue these studies. John Seely Brown, as Area Manager for the Cognitive and Instructional Sciences, has had a major impact on us by creating a stimulating intellectual environment of cognitive scientists around us.

Don Norman and Richard Young provided extensive substantive comments on the research reported in the book. Many productive discussions with colleagues have influenced our thinking and helped us formulate our position. They include: George Baylor, John Black, Danny Bobrow, Ross Bott, Ted Crossman, Jerry Elkind, Austin Henderson, Ron Kaplan, Tom Malone, Jim Morris, William Newman, Beau Sheil, Larry Tesler, and Mike Williams. Several students, working with us at PARC, have kept us on our toes: Terry Roberts, Marilyn Mantei, Jarrett Rosenberg, Allen Sonafrank, Lucy Suchman, Keith Patterson, Kathy Hemenway, Brian Ross, Sally Douglas, Frank Halasz, and Carolyn Foss.

Ralph Kimball, Robin Kinkead, Bill Bewley, and Bill Verplank—in the development divisions of Xerox—gave us valuable advice and helped us test some of the models in this book. Steve Smith and Shmuel Oren provided mathematical consulting. Warren Teitelman and Larry Masinter provided programming help in Interlisp (Teitelman, 1978), the system in which all of our analysis and simulation programs are written. Ron Kaplan and Beau Shiel provided statistical consultation for the analysis of our data and help in using the Interactive Data-analysis Language (Kaplan, Sheil, and Smith, 1978), their statistical analysis system written in Interlisp.

Our experimental work would not have been possible without help and support in building and maintaining our laboratory systems and equipment. Bill Duvall and George Robertson implemented our experiment-running systems; and Jim Mayer, Bill Winfield, and others kept our equipment running. The large amount of experimentation and detailed analysis would not have been possible without the help of several research assistants over the years: Betty Burr, Janet Farness, Steve Locke, Marilyn Mantei, Beverly McHugh, Terry Roberts, Rachel Rutherford, and Betsey Summers.

Many others at PARC have also been of help. Chris Jeffers and Jeanie Treichel provided administrative backing. Barbara Baird, Connie Redell, Malinda Maggiani, and Jackie Guibert provided secretarial support. Giuliana Lavendel and her library staff tracked down many obscure references for us.

A number of people have helped directly with the production of the book. Rachel Rutherford helped edit the text and brought to light numerous errors, inconsistencies, and infelicities of expression. Betsey Summers, Steve Locke, and Leslie Keenan helped manage and proof the text and figures. Bill Bowman gave graphics advice on several figures. Lyle Ramshaw guided us through the intricacies of various document preparation systems. Terri Doughty helped us format the text and tables for galley printing. The galleys for the book were printed on an experimental phototypesetting printer developed at PARC.

In the preparation of this book—much of it about text-editing—we have ourselves been heavy users of the computer text-editors. We have spent several thousands of hours text-editing on BRAVO (one of the systems we describe in the book) at tasks similar to those we have studied on our subjects, performing perhaps a million editing tasks in the process. From this experience and study, we have a great appreciation for the display-based text-editing technology that our colleagues at PARC have been able to fashion.

We have no doubt missed some people who deserve mention. One advantage of writing a book of this kind is that our excuse—that human information-processing systems are limited—is contained herein. As we explain in Chapter 2, searching Long-Term Memory requires considerable effort, and we have not managed to move the full way along the information retrieval curve pictured in Figure 2.27.

SC, TM, AN
Palo Alto
October 1982

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To JJ, Lydia, and Noël

1. An Applied Information-Processing Psychology

A scientific psychology should not only help us to understand our own human nature, it should help us in our practical affairs. In educating our children, it should help us to design environments for learning. In building airplanes, it should help us to design for safety and efficiency. In staffing for complex jobs, it should help us to discover both the special skills required and those who might have them. And on and on. Given the breadth of environments we design for ourselves, there is no limit to the number of domains where we might expect a scientific knowledge of human nature to be of use.

The domain of concern to us, and the subject of this book, is how humans interact with computers. A scientific psychology should help us in arranging this interface so it is easy, efficient, error-free—even enjoyable.

Recent advances in cognitive psychology and related sciences lead us to the conclusion that knowledge of human cognitive behavior is sufficiently advanced to enable its applications in computer science and other practical domains. The years since World War II have been the occasion for an immense wave of new understandings and new techniques in which man has come to be viewed as an active processor of information. In the last decade or so, these understandings and techniques have engulfed the main areas of human experimental psychology[1]: perception,[2] performance,[3] memory,[4] learning,[5] problem solving,[6] psycholinguistics.[7] By now, cognitive psychology has come to be dominated by the information-processing viewpoint.

A major advance in understanding and technique brings with it, after some delay, an associated wave of applications for the new knowledge. Such a wave is about to break in psychology. The information-processing view will lead to a surge of new ways for making psychology relevant to our human needs. Already the concepts of information-processing psychology have been applied to legal eyewitness testimony[8] and to the design of intelligence tests.[9] And in the study of man-machine systems and engineering psychology, it has for some time been common to include a block diagram of the overall human information-processing system in the introductory chapter of textbooks,[10] even though the reach of that block diagram into the text proper is still tenuous. There are already the beginnings of a subfield, for which various names (associating the topic in different ways) have been suggested: user sciences,[11] artificial psycholinguistics,[12] cognitive ergonomics,[13] software psychology,[14] user psychology,[15] and cognitive engineering.[16]

[1] For representative examples see Lindsay and Norman's (1977) *Human Information Processing*, Anderson's (1980) *Cognitive Psychology and its Implications*, the *Handbook of Learning and Cognitive Processes* (Estes, ed. 1975-1978), the *Attention and Performance* collections of papers (Kornblum, 1973; Rabbitt and Dornič, 1975; Dornič, 1977; Requin, 1978; Long and Baddeley, 1981), and the journal *Cognitive Psychology*.

[2] Examples: Broadbent (1958), *Perception and Communication*; Green and Swets (1966), *Signal Detection Theory and Psychophysics*; Neisser (1967), *Cognitive Psychology*; Cornsweet (1970) *Visual Perception*.

[3] Examples: Fitts and Posner (1967), *Human Performance*; Welford (1968), *Fundamentals of Skill*; Kintsch (1974), *The Representation of Meaning in Memory*; Tversky (1977), "Feature of similarity"; Posner (1978), *Chronometric Explorations of the Mind*.

[4] Examples: Anderson and Bower (1973), *Human Associative Memory*; Baddeley (1976), *The Psychology of Memory*; Crowder (1976), *Principles of Learning and Memory*; Murdock (1974), *Human Memory, Theory and Data*.

[5] Examples: Fitts (1964), "Perceptual-motor skill learning"; Klahr and Wallace (1976), *Cognitive Development: An Information-Processing View*; Anderson (1981a), *Cognitive Skills and their Acquisition*.

[6] Example: Newell and Simon (1972), *Human Problem Solving*.

Our own goal is to help create this wave of application: to help create an applied information-processing psychology. As with all applied science, this can only be done by working within some specific domain of application. For us, this domain is the human-computer interface. The application is no offhand choice for us, nor is the application dictated solely by its extrinsic importance. There is nothing that drives fundamental theory better than a good applied problem, and the cognitive engineering of the human-computer interface has all the markings of such a problem, both substantively and methodologically. Society is in the midst of transforming itself to use the power of computers throughout its entire fabric—wherever information is used—and that transformation depends critically on the quality of human-computer interaction. Moreover, the problem appears to have the right mixture of industrial application and symbol manipulation to make it a "real-world" problem and yet be within reasonable reach of an extended cognitive psychology. In addition, we have personal disciplinary commitments to computer science as well as to psychology.

This book reports on a program of research directed towards understanding human-computer interaction, with special reference to text-editing systems. The program was undertaken as an initial step towards the applied information-processing psychology we seek. Before outlining individual studies, it is appropriate to sketch how this effort fits in with the larger endeavor.

[7] Example: Clark and Clark (1976), *Psychology and Language: An Introduction to Psycholinguistics.*

[8] Loftus (1979).

[9] Hunt, Frost, and Lunneborg (1973).

[10] Sheridan and Ferrell (1974); McCormick (1976).

[11] Vallee (1976).

[12] Sime and Green (1974).

[13] Sime, Fitter, and Green (1975).

[14] Shneiderman (1980).

[15] Moran (1981*a*).

[16] Norman (1980).

1.1. THE HUMAN-COMPUTER INTERFACE

The human-computer interface is easy to find in a gross way—just follow a data path outward from the computer's central processor until you stumble across a human being (Figure 1.1). Identifying its boundaries is a little more subtle. The key notion, perhaps, is that the user and the computer engage in a communicative dialogue whose purpose is the accomplishment of some task. It can be termed a dialogue because both the computer and the user have access to the stream of symbols flowing back and forth to accomplish the communication; each can interrupt, query, and correct the communication at various points in the process. All the mechanisms used in this dialogue constitute the interface: the physical devices, such as keyboards and displays, as well as computer's programs for controlling the interaction.

At any point in the history of computer technology there seems to be a prototypical user interface. A few years ago it was the teletypewriter; currently it is the alphanumeric video-terminal. But the actual diversity is now much greater. All so-called "remote entry" devices count as interfaces; and a large number of such specialized devices exist in the commercial and industrial world to record sales, maintain inventory records, or control industrial processes. Almost all such devices are fashioned from the same basic sorts of components (keyboards, buttons, video displays, printers) and connect to the same sorts of information-processing mechanisms (disks, channels, interrupt service routines).

The very existence of the direct human-computer interface is itself an emergent event in the development of computers. If we go back twenty years, the dominant scheme for entering information into a computer consisted of a trio of people. First there was the user, someone who wanted to accomplish some task with the aid of the computer. The user encoded what he wanted onto a coding sheet, then sent it to a second person, the keypunch operator, who used an off-line device, the keypunch, to create a deck of punched cards that encoded the same information in a different form. The cards in turn went to a third person, the computer-operator, who entered the cards into the computer via the card reader. The computer then responded by printing messages and data on paper for the operator to gather up and send back to the user. The relationship between the user and the computer was sufficiently remote that it should be likened more to a literary correspondence than to a conversational dialogue. It is the general

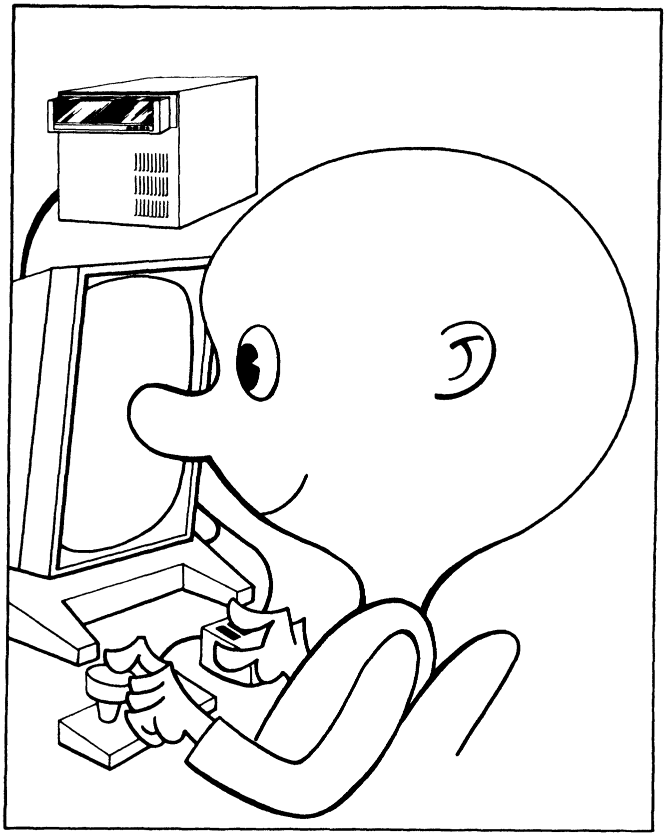

Figure 1.1. The human-computer interface.

demise of such arrangements involving human intermediaries, and the resultant coupling of the user directly to the computer, that has given rise to the contemporary human-computer interface. Whatever continued evolution the interface takes—and it will be substantial—human-computer interaction is unlikely ever to lose this character of a conversational dialogue.

Of course, there is much more to improving computer interfaces than simply making them conversational. Informal evidence from the direct experience of users provides numerous examples of current interface deficiencies:

> In one text-editing system, typing the word *edit* while in command mode would cause the system to select every-

> thing, delete everything, and then insert the letter t (this last making it impossible to use the system Undo command to recover the deleted text because only the last command could be undone).
>
> In another text-editing system, so many short commands were defined that almost any typing error would cause some disaster to happen. For example, accidentally typing CONTROL-E would cause the printer to be captured by the user. Since no indication of this event was given, no other users would be permitted to print until the other users eventually discovered who had the printer. In an even more spectacular instance, accidentally typing CONTROL-Z would delete all the user's files—permanently.
>
> In one interactive programming system, misspelling a variable name containing hyphens (a common way of marking off parts of a name) would cause the system to rewrite the user's program, inserting code to subtract the parts of the name. In many cases, the user would have to mend his program by hand, laboriously searching for and editing the damaged code.
>
> In a set of different subsystems meant to be used together, the name "List" was given to many different commands, each having a different meaning: (1) send a file to the printer to make a hardcopy, (2) show the directory of files on the display, (3) show the content of a file on the display, (4) copy the workspace to a file, (5) create a particular kind of data structure.

Yet, when one looks at the teletype interfaces of yesterday, it is clear that substantial progress has been made. The emergence of the direct human interface, circumventing the keypuncher and operator, must itself be counted as an improvement of enormous value. We now have interfaces that allow the use of computers for such highly interactive tasks as making engineering drawings and taking airline reservations. But despite considerable advancements, the systems we have are often ragged and in places are sufficiently poor to cripple whole ranges of use.

What strikes one most noticeably about existing interfaces, besides all the little ways they fail, is that their failures appear to be unnecessary. Why, when interaction could be so smooth, even elegant, is it often so rough, even hazardous? Two observations may help explain this perplexing state of affairs.

First, interaction with computers is just emerging as a human activity. Prior styles of interaction between people and machines—such as driver and automobile, secretary and typewriter, or operator and control room—are all extremely lean: there is a limited range of tasks to be accomplished and a narrow range of means (wheels, levers, and knobs) for accomplishing them. The notion of the *operator* of a machine arose out of this context. But the user is not an operator. He does not operate the computer, he communicates with it to accomplish a task. Thus, we are creating a new arena of human action: communication *with* machines rather than operation *of* machines. What the nature of this arena is like we hardly yet know. We must expect the first systems that explore the arena to be fragmentary and uneven.

Second, the radical increase in both the computer's power and its performance/cost ratio has meant that an increasing amount of computational resources have become available to be spent on the human-computer interface itself, rather than on purely computational tasks. This increase of deployable resources exacerbates the novelty of the area, since entirely new styles of interaction become available coincidentally with an increased amount of computational ability available per interaction. These new styles often lead to completely new interfaces, which are then even more ragged than before. At the same time, opportunities for the invention of good interfaces also increase rapidly, accounting for the leaps and bounds we have seen in terms of major improvements in functionality and ease of use.

1.2. THE ROLE OF PSYCHOLOGY

Many in the computer field agree that there is an obvious way to design better human-computer interfaces. Unfortunately, they disagree on what it is. It is obvious to some that psychological knowledge should be applied. Their slogan might be, in the words of Hansen (1971): "Know the user!" It is obvious to others that the interface should simply be designed with more care—that if designers were given the goal of good interfaces, rather than stringent cost limits or tight deadlines, then they would produce good designs. Their slogan might be: "Designers are users too—just give them the time and freedom to design it right!" And it is obvious to others still that one should pour the effort into some new components—flat displays, color graphics, or dynamically codeable microprocessors in the terminal. Their slogan might be: "Make the components good enough and the system will take care of itself!"

Who is to gainsay each of these their point? The technology limits, often severely, what can be done. All the human engineering in the world will not turn a 10-character-per-second teletypewriter into a high-resolution graphics terminal. The history of terminal development so far is writ largely in terms of advances in basic interface components, most notably the resources to allow substantial computational cycles to be devoted to the interface. It is easy to point to current limitations whose lifting will improve the interface by orders of magnitude. Immense gains will occur when the display holds not the common 24 × 80 characters (the typical alphanumeric video terminal, widely available today), but a full page of 64 × 120 characters (the typical 1000 × 800 pixel video terminal, available at a few places today), or even the full drafting board of 512 × 512 characters (not really available anywhere, yet, as far as we know).

Moreover, any accounting will have to credit the majority of the capabilities and advances at the interface to design engineers and only a few of them to psychologists. However many imperfections there remain in the interface, the basic capabilities and inspired creations that do exist came out of an engineering analysis of the functions needed and the fact that the designer, being human, could empathize directly with the user.

And yet, there remain the mini-horror stories—of systems where, after the fact, it became clear that either the nature or the limitations of the user were not appreciated, and some design foolishness was committed. Since it is these stories that come to mind in discussing the role of the human at the interface, it is often assumed that all that one needs are ways of checking to be sure that the obvious is not overlooked; "All we need from psychology is a few good checklists!" might be the slogan here. But as we shall see, there is more to human-computer interaction than can be caught with checklists.

The role psychology might be expected to play in the design of the user-computer interface is suggested by the results it was able to achieve for military equipment during World War II. At that time, it had become apparent that a strong limiting factor in realizing the potential of man-machine systems, such as radar sets and military aircraft, lay in the difficulty of operating the equipment. Out of a wartime collaboration between natural scientists, engineers, and psychologists came major advances, not only with respect to the man-machine systems being designed, but also with respect to psychological theory itself. Examples of the latter include the theory of signal detection, manual control theory, and a methodology for the design of cockpit instrument displays. That with psychological attention to human performance airplanes became more flyable encourages us to believe that with psychological attention to human performance computers can become more usable.

1.3. THE FORM OF AN APPLIED PSYCHOLOGY

What might an applied information-processing psychology of human-computer interfaces be like and how might it be used? Imagine the following scenario:

> A system designer, the head of a small team writing the specifications for a desktop calendar-scheduling system, is choosing between having users type a key for each command and having them point to a menu with a lightpen. On his whiteboard, he lists some representative tasks users of his system must perform. In two columns, he writes the steps needed by the "key-command" and "menu" options. From a handbook, he culls the times for each step, adding the step times to get total task times. The key-command system takes less time, but only slightly. But, applying the analysis from another section of the handbook, he calculates that the menu system will be faster to learn; in fact, it will be learnable in half the time. He has estimated previously that an effective menu system will require a more expensive processor: 20% more memory, 100% more microcode memory, and a more expensive display. Is the extra expenditure worthwhile? A few more minutes of calculation and he realizes the startling fact that, for the manufacturing quantities anticipated, training costs

> for the key-command system will exceed unit manufacturing costs! The increase in hardware costs would be much more than balanced by the decrease in training costs, even before considering the increase in market that can be expected for a more easily learned system. Are there advantages to the key-command system in other areas, which need to be balanced? He proceeds with other analyses, considering the load on the user's memory, the potential for user errors, and the likelihood of fatigue. In the next room, the Pascal compiler hums idly, unused, awaiting his decision.

The system designer is engaged in a sort of psychological civil engineering, trading computed parameters of human performance against cost and other engineering variables. The psychological science base necessary to make possible his design efforts is the sort of applied psychology that is the topic of this book. Such a psychology must necessarily be homogeneous in form with the rest of the engineering science base to allow tradeoffs between psychological and other design considerations. To be useful, we would argue, such a psychology must be based on task analysis, calculation, and approximation.

Task Analysis. When psychology is applied in the context of a specific task, much of the activity hardly seems like psychology at all, but rather like an analysis of the task itself. The reason for this is clear: humans behave in a goal-oriented way. Within their limited perceptual and information-processing abilities, they attempt to adapt to the task environment to attain their goals. Once the goals are known or can be assumed, the structure of the task environment provides a large amount of the predictive content of psychology.

Calculation. The ability to do calculations is the heart of useful, engineering-oriented applied science. Without it, one is crippled. Applications are, of course, still possible, as witness mental testing, behavior modification, assertiveness training, and human-factors investi-gations of display readability. But what is needed to support an engineering analysis are laws of parametric variation, applicable on the basis of a task analysis.

Psychology is not strong on calculation, though a few useful laws, such as Power Law of Practice, exist. The reason might be thought to be an inherent characteristic of psychology, or maybe even more generally, of all human sciences. Our view is the opposite. Psychology is largely non-calculational because it has followed a different drummer. It has been excessively concerned with hypothesis testing—with building techniques to discriminate which of two ideas is right. If one changes what one wants from the science, one will find the requisite techniques. Interestingly, a branch of the human sciences, work-measurement industrial engineering, indeed asked a different question—namely, how long would it take people to do preset physical tasks—and it obtained useful answers.

Approximation. If calculations are going to be made rapidly, they are necessarily going to be over-simplified. Nature—especially human nature—is too complex to be written out on the back of an envelope. But in engineering, approximations are of the essence. It is vital to get an answer good enough to dictate the design choice; additional accuracy is gilding the computational lily.

Again, psychology has in general not asked after approximations, though it has certainly learned to talk in terms of simplified models. The neglect of approximation has been especially encouraged by the emphasis on statistical significance rather than on the magnitude of an effect. A difference of a few percent in performance at two levels of an independent variable is usually of little practical importance and can often be ignored in an approximation, even if the difference is highly significant statistically. But if there is no external criterion—no design decision to be made, for instance—then there is no way to tell which approximations are sufficient.

But, whereas an applied psychology of human-computer interaction should be characterized by task analysis, calculation, and approximation, these are not the only considerations. It is obvious that an applied psychology intended to support cognitive engineering should also be relevant to design. It is less obvious, but nonetheless true, that to be successful, an applied psychology should be theory-based.

RELEVANT TO DESIGN

Design is where the action is in the human-computer interface. It is during design that there are enough degrees of freedom to make a difference. An applied psychology brought to bear at some other point is destined to be half crippled in its impact.

We suspect that many psychologists would tend to pick evaluation as the main focus for application (though some might have picked training). Evaluation is what human factors has done best. Given a real system, one can produce a judgment by experimentation. Thus, the main tool in the human-factors kit has been the methodology of experimental design, supported by concomitant skill in experimental control and in statistics with which to assess the results. The emphasis on evaluation is widespread: There is a whole subfield of psychology whose concern is to evaluate social action programs. The testing movement is fundamentally evaluational in character, whether concerned with intelligence testing or with clinical assessment.

Applying psychology to the evaluation of systems is assuredly easier than applying it to the design of systems. In evaluation, the system is given; all its parts and properties are specified. In design, the system is still largely hypothetical; it is a class of systems. On the other hand, there is much less leverage in system evaluation than in system design. In design, one wants results expressed explicitly as a function of some controllable parameters, in order to explore optimization and sensitivity. In evaluation, this urge is much diminished; experimental evaluation is so expensive as to be prohibitive, permitting exploration of only two or three levels of each independent variable. Most importantly, by the time a system is running well enough to evaluate, it is almost inevitably too late to change it much. Thus, an applied psychology aimed exclusively at evaluation is doomed to have little impact.

There are several choices for how to institutionalize an applied psychology. First, psychologists could be the primary professionals in the field. Though possible in some fields, such as mental health, counseling, or education, we think this arrangement unlikely for computers. The field is already solely in the possession of computer engineers and scientists. Second, psychologists could be specialists, either as members of separate human-factors units within the organizations or as another individual specialty within the primary design team. Our reasons for not favoring separate psychology units reflect the additional separation we believe they imply between the psychology and the development of interfaces. Application of psychology would shift too strongly towards evaluation and away from the main design processes.

We favor a third choice: that the primary professionals—the computer system designers—be the main agents to apply psychology. Much as a civil engineer learns to apply for himself the relevant physics of bridges, the system designer should become the possessor of the relevant applied psychology of human-computer interfaces. Then and only then will it become possible for him to trade human behavioral considerations against the many other technical design considerations of system configuration and implementation. For this to be possible, it is necessary that a psychology of interface design be cast in terms homogeneous with those commonly used in other parts of computer science and that it be packaged in handbooks that make its application easy. Thus, the system designer in our scenario finds the design handbook more efficient to use than plunging blindly into code with his Pascal compiler, although he may still find it profitable to engage in exploratory implementation.

THEORY-BASED

An applied psychology that is theory-based, in the sense of articulating a mechanism underlying the observed phenomena, has advantages of insight and integration over a purely empirical approach. The point can be made by reference to two examples of behavioral science lacking a strong theory in this sense: work-study industrial engineering, referred to earlier, and intelligence testing. Rather than develop the theory of skilled movement, the developers of the several movement time systems chose an empirical approach, tabulating the times to make various classes of movements and ignoring promising theoretical developments such as Fitts's Law (at least until recently). Although their tables of motion times ran to four significant figures, they ignored the variance of the times and interactions between sequential motions, thus rendering the apparent precision illusory. This lack of adequate theoretical development made the work, despite its impressive successes, vulnerable to attacks from outside the field (see Abruzzi, 1956; Schmidtke and Stier, 1961). Similarly, in mental testing, the lack of a psychological theory of the mental mechanisms underlying intelligence (as opposed to a purely statistical theory of test construction) has put the validity of mental tests in doubt despite, again, impressive successes.

It is natural for an applied psychology of human-computer interaction to be based theoretically on information-processing psychology, with the latter's emphasis on mental mechanism. The use of models in which man is viewed as a processor of information also provides a common framework in which models of memory, problem solving, perception, and behavior all can be integrated with one another. Since the system designer also does his work in information-processing terms, the emphasis is doubly appropriate. The lack of this common framework is one reason why it would be difficult to meld in important techniques such as the use of Skinnerian contingent reinforcement. It is not that the techniques are not useful in general, nor that they cannot be applied to the problems of the human-computer interface; but within the framework that underlies this book, they would show up as isolated techniques.

The psychology of the human-computer interface is generally individual psychology: the study of a human behaving within a non-human environment (though, interestingly, interacting with another active agent). But within the study all psychological functioning is included—motor, perceptual, and cognitive. Whereas much psychology tends to focus on small micro-tasks studied in isolation, an applied psychology must dwell on the way in which all the components of the human processor are integrated over time to do useful tasks. For example, it might take into account interactions among the following: the ease with which commands can be remembered, the type font of characters as it affects legibility of the commands, the number of commands in a list, and anything else relevant to the particular interface. The general desirability of such wide coverage has never been in doubt. It appears in our vision of an applied psychology because wide coverage, especially the incorporation of cognition, now seems much more credible than it did twenty years ago. On the other hand, motivational and personality issues are not included. Again, there is hardly any doubt of the desirability of including them in an applied psychology, but it is unclear how to integrate the relevant existing knowledge of these topics.

1.4. THE YIELD FOR COGNITIVE PSYCHOLOGY

The textbook view is that as a science develops it sprouts applications, that knowledge flows from the pure to the applied, that the backflow is the satisfaction (and support) that comes to a science from benefiting society. We have been reminded often enough that such a view does violence to the realities in several ways. Applied domains have a life and source of their own, so that many ingenious applications do not spring from basic science, but from direct understanding of the task in an applied context—from craft and experience. More importantly in the present context, applied investigations vitalize the basic science; they reveal new phenomena and set forth clearly what it is that needs explanation. The mechanical equivalent for heat, for instance, arose from Count Rumford's applied investigations into the boring of brass cannon; and the bacteriological origin of common infectious diseases eventually arose, in part, out of studies by Pasteur on problems besetting the fermentation of wine. The basic argument was made for psychology by Bryan and Harter (1898); and numerous applied psychological models exist to remind us of what is possible (for example, Bryan and Harter's 1898 and 1899 studies of telegraphy, Book's 1908 studies of typewriting, and Dansereau's 1968 study of mental arithmetic).

These general points certainly hold for an applied cognitive psychology, and on the same general ground that they hold for all sciences. However, it is worth detailing the three main yields for cognitive psychology that can flow from a robust applied cognitive psychology.

The first contribution is to the substance of basic cognitive psychology. The information-processing revolution in cognitive psychology is just beginning. Many domains of cognitive activity have hardly been explored. Such explorations are not peripheral to the basic science. It is a major challenge to the information-processing view to be able to explain how knowledge and skill are organized to cope with all kinds of complex human activities. Each application area in fact becomes an arena in which new problems for the basic science can arise. Each application area successfully mastered offers lessons about the ways in which the basic science can be extended to cover new areas. Ultimately, as a theory becomes solidified, application areas contribute less and less to the basic science. But at the beginning, just the reverse is true.

The domain of human-computer interaction is an example of such an unexplored domain. It has strong skill components. People who interact with computers extensively build up a repertoire of efficient, smooth, learned behaviors for carrying out their routine communicative activities. Yet, the interaction is also intensely cognitive. The skills are wielded within a problem-solving context, and the skills themselves involve the processing of symbolic information. As we shall see in abundance, even the most routine of these activities, such as using a computer text-editing program, requires the interpretation of instructions, the formulation of sequences of commands, and the communication of these commands to the computer.

The second contribution is to the style of cognitive psychology rather than to its substance. We believe that the form of the psychology of human-computer interaction, with its emphasis on task analysis, calculation, and approximation, is also appropriate for basic cognitive psychology. The existing emphasis in psychology on discriminating between theories is certainly understandable as a historical development.

However, it stifles the growth of adequate theory and of the cumulation of knowledge by focusing the attention of the field on the consequences of theories, however uninteresting in themselves, that can be used to tell whether idea A or idea B is correct. Measurements come to have little value in themselves as a continually growing body of useful quantitative knowledge of the phenomena. They are seen instead primarily as indicators fashioned to fit the demands of each experimental test. Since there is no numerical correspondence across paradigms in what is measured, the emphasis on discrimination fosters a tendency towards isolation of phenomena in specific experimental paradigms.

The third contribution is simply that of being a successful application, though it sounds a bit odd to say it that way. Modern cognitive psychology has been developing now for 25 years. If information-processing psychology represents a successful advance of some magnitude, then ultimately it must both affect the areas in which psychology is now applied and generate new areas of application.

1.5. THE YIELD FOR COMPUTER SCIENCE

It is our strong belief that the psychological phenomena surrounding computer systems should be part of computer science. Thus, we see this book not just as a book in applied psychology, but as a book in computer science as well. When university curriculum committees draw up a list of "what every computer scientist should know to call himself a computer scientist," we think models of the human user have a place alongside models of compilers and language interpreters.

The fundamental argument is worth stating: Certain central aspects of computers are as much a function of the nature of human beings as of the nature of the computers themselves. The relevance of both computer science and psychology to the design of programming languages and the interface is easy to argue, but psychological considerations enter into more topics in computer science than is usually realized. The presumption that has governed two generations of operating systems, for instance, that time-sharing systems should degrade response time as the number of users increases, is neither dictated by technology nor independent of the psychology of the user. A sufficiently crisp model of the effects of such a feature on the user could have turned the course of development of operating systems into quite different channels of development (into the logic of guaranteed service, contracted service, or proportionately graded services, for example). The yield for computer science that can flow from an applied psychology of human-computer interaction is engineering methods for taking the properties of users into account during system design.

1.6. PREVIEW

In this book, we report on a series of studies undertaken to understand the performance of users on interactive computing systems. Since new knowledge and insight are often achieved by first focusing on concrete cases and then generalizing, we direct a major portion of our effort towards user performance on computer text-editing systems. From this beginning, we try to generalize to other systems and to cognitive skill generally. We address four basic questions: (1) How can the science base be built up for supporting the design of human-computer interfaces? (2) What are user performance characteristics in a specific human-computer interaction task domain, text-editing? (3) How can our results be cast as practical models to aid in design? (4) What generalizations arise from the specific studies, models, and applications?

SCIENCE BASE

Chapter 2 begins by discussing the existing scientific base on which to erect an applied psychology of the human-computer interface. It does not review all the sources in their own terms—what is available from cognitive psychology, human factors, industrial engineering, manual control, or the classical study of motor skills—rather, it lays out a model of the human information-processor that is suited to an applied psychology and justified by current research.

TEXT-EDITING

Attention then turns to a detailed examination of text-editing as a prototypical example of human-computer interaction. An elementary requirement for understanding behavior at the interface is some gross quantitative information about user behavior, to provide a background picture against which to place more detailed studies in context. The three studies in Chapters 3 and 4 provide such a picture. Two of these (Chapter 3), a benchmark study comparing text-editing systems and a study of the individual user differences, allow one to assess the variability in performance time arising from editing system design and from individual user differences. The third study (Chapter 4) uses the data of Chapter 3 to explore how well a simple model, in which all editing modifications are assumed to take the same time, does at analyzing tradeoffs between using a computer text-editor vs. using a typewriter.

The next three chapters develop an information-processing model for the behavior of users with an editing system. Chapter 5 introduces the basic theory. The user is taken to employ goals, operators, methods, and selection rules for the methods (the GOMS analysis) to accomplish an editing task from a marked-up manuscript. Experimental verification of the analysis is given, and the effect on accuracy due to the detail with which the analysis is applied is also investigated. The routine use of an editing system is discussed as an instance of cognitive skill. Chapter 6 extends the model in three ways. First, the model is reduced to a complete, running computer simulation of user performance. Second, the analysis is extended to user behavior on a display-oriented system. Third, stochastic elements are introduced into the model to predict the distributions of performance times. Chapter 7 examines in detail one suboperation of editing: selecting a piece of text. Four different devices for doing this are tested, and a theoretical account is given for their performance.

ENGINEERING MODELS

Chapters 8 and 9 focus on the ways in which the GOMS analysis can be simplified to provide practical models for predicting the amount of time required by a user to do a task. In Chapter 8, a model at the level of individual keystrokes is presented that is sufficiently simple and accurate to be a design tool. The model is validated over several systems, tasks, and users; and examples are given for ways in which the model could be used in engineering applications. In Chapter 9, a second simplification of the GOMS analysis, this time at a more gross level, is presented This model is suited for cases where, as in the early stages of design, the system to be analyzed is not fully specified.

EXTENSIONS AND GENERALIZATIONS

So far, the studies have focused mostly on manuscript editing and on similar tasks where the user carries out a set of instructions. Chapter 10 extends the same kind of analysis to a particular problem-solving activity:

the use of a computer system to lay out a VLSI electronic circuit. The analysis shows that the user behavior exhibits many of the characteristics of manuscript editing and that the behavior is indeed a routine cognitive skill, partially understandable in terms of the concepts already introduced.

Chapter 11 attempts to place results from the above studies in a larger theoretical context. It continues the discussion of text-editing as an instance of cognitive skill and the relationship between cognitive skill generally and problem solving. Chapter 12 addresses the role of psychological studies in design. It is argued that psychological studies should emphasize the creation of performance models. The several methods of doing this are discussed and provide a framework for summarizing the thrust of the present book. A number of guidelines for systems development that arise from our studies are listed.

References

Abruzzi, A. (1952). Work Measurement. New York: Columbia University Press.
Abruzzi, A. (1956). Work, Workers, and Work Measurement. New York: Columbia University Press.
Akin, O. , and Chase, W. (1978). Quantification of three-dimensional structures. Journal of Experimental Psychology 4, 397–410.
Alden, D.G. , Daniels, R.W. , and Kanarick, A. (1972). Keyboard design and operation: A review of the major issues. Human Factors 14, 275–293.
Anandan, P. , Embley, D.W. , and Nagy, G. (1980). An application of file-comparison algorithms to the study of program editors. International Journal of Man-Machine Studies 13, 201–211.
Anderson, J.R. (1976). Language Memory and Thought. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Anderson, J.R. (1980). Cognitive Psychology and its Implications. San Francisco: W.R. Freeman.
Anderson, J.R. , ed. (1981a). Cognitive Skills and their Acquisition. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Anderson, J.R. (1981b). Acquisition of Cognitive Skills. Technical Report, Department of Psychology, Camegie-Mellon University.
Anderson, J.R. , and Bower, G.H. (1973). Human Associative Memory. Washington, D.C.: V.H. Winston and Sons.
Atkinson, R.C. , and Shiffrin, R.M. (1968). Human memory: A proposed system and its control processes. The Psychology of Learning and Motivation 2, 89–195.
Atwood, M.E. See Ramsey and Atwood (1979); Ramsey , Atwood , and Kirshbaum (1978).
Averbach, E. , and Coriell, A.S. (1961). Short-term memory in vision. Bell System Technical Journal 40, 309–328.
Baddeley, A.D. (1966). Short-term memory for word sequences as a function of acoustic, semantic and formal similarity. Quarterly Journal of Experimental Psychology 18, 362–365.
Baddeley, A.D. (1976). The Psychology of Memory. New York: Basic Books.
Baddeley, A.D. (1981). The concept of working memory: A view of its current state and probably future development. Cognition, 10 17–23.
Baddeley, A.D. See also Long and Baddeley (1981).
Bamaby, J.R. See Myer and Bamaby (1973).
Barnard, P.J. , Hammond, N.V. , Morton, J. , Long, J.B. , and Clark, I.A. (1981). Consistency and compatibility in human-computer dialogue. International Journal of Man-Machine Studies 15, 87–134.
Baron, S. See Pew , Baron , Feehrer , and Miller (1977).
Bartlett, F.C. (1958). Thinking. London: Allen and Unwin.
BBN (1973). TENEX Text Editor and Corrector Manual. Cambridge, Massachusetts: Bolt, Beranek, and Newman Bell, G. See Siewiorek , Bell , and Newell (1981).
Belmont, L. , and Birch, H.G. (1951). Re-individualizing the repression hypothesis. Journal of Abnormal & Social Psychology, 46 226–235.
Bennett, J. (1972). The user interface in interactive systems. Annual Review of Information Science and Technology 7, 159–196.
Berman, M.L. See English, Englebart, and Berman (1967).
Bernbach, H.A. (1970). A multiple-copy model for post perceptual memory. In D.A. Norman , ed., Models of Human Memory, 103–116, New York: Academic Press.
Birch, H.G. See Belmont and Birch (1951).
Bisseret, A. See Sperandio and Bisseret (1974).
Blankenship, A.B. (1938). Memory span: A review of the literature. Psychological Bulletin 35, 1–25.
Blumenthal, A.L. (1977). The Process of Cognition. Englewood Cliffs, New Jersey: Prentice-Hall.
Bloch, A.M. (1885). Expérience sur la vision. Comptes Rendus de Séances de la Société de Biologie (Paris) 37, 493–495.
Bobrow, D. , and Raphael, B. (1974). New programming languages for artificial intelligence research. Computing Surveys 6, 155–174.

Bobrow, D. See also Norman and Bobrow (1975).
Boies, S.J. (1974). User behavior on an interactive computer system. IBM Systems Journal 13, 2–18.
Boies, S.J. See also Posner , Boies , Eichelman , and Taylor (1969).
Book, W.F. (1908). The psychology of skill with special reference to its acquisition in typewriting. University of Montana Studies in Psychology I. Reprinted, New York: Gregg, 1925.
Bower, G.H. See Anderson and Bower (1973).
Breitmeyer, B.G. , and Ganz, L. (1976). Implications of sustained and transient channels for theories of visual pattern masking, saccadic suppression, and information processing. Psychological Review, 83 1–36.
Broadbent, D.E. (1958). Perception and Communication. London: Pergamon Press.
Brooks, R. (1977). Towards a theory of the cognitive processes in computer programming. International Journal of Man-Machine Studies 9, 737–751.
Brown, J.S. , and Vanlehn, K. (1980). Repair theory: A generative theory of bugs in procedural skills. Cognitive Science 4, 379–426.
Bryan, W.L. , and Harter, N. (1898). Studies in the physiology and psychology of the telegraphic language. Psychological Review 4, 27–53.
Bryan, W.L. , and Harter, N. (1899). Studies on the telegraphic language, the acquisition of a hierarchy of habits. Psychological Review 6, 345–375.
Burr, B.J. See Card , English , and Burr (1978).
Busswell, G.T. (1922). Fundamental reading habits: A study of their development. Education Monographs (Supplement) 21.
Cakir, A. , Hart, D.J. , and Stewart, T.F.M. (1980). Visual Display Terminals. New York: Wiley.
Calfee, R.C. (1975). Human Experimental Psychology. New York: Holt, Rinehart, and Winston.
Card, S.K. (1978). Studies in the Psychology of Computer Text-editing Systems. Ph. D. Thesis, Department of Psychology, Carnegie-Mellon University.
Card, S.K. , English, W.K. , and Burr, B.J. (1978). Evaluation of mouse, rate-controlled isometric joystick, step keys, and text keys for text selection on a CRT. Ergonomics 21, 601–613.
Card, S.K. , Moran, T.P. , and Newell, A. (1976). The Manuscript Editing Task: A Routine Cognitive Skill. Palo Alto, California: Xerox Palo Alto Research Center, Technical Report SSL-76-8.
Card, S.K. , Moran, T.P. , and Newell, A. (1980a). Computer text-editing: An information-processing analysis of a routine cognitive skill. Cognitive Psychology 12, 32–74.
Card, S.K. , Moran, T.P. , and Newell, A. (1980b). The Keystroke-Level Model for user performance time with interactive systems. Communications of the ACM 23, 396–410.
Card, S.K. See also Moran and Card (1982).
Carlton, L.G. (1980). Movement control characteristics of aiming responses. Ergonomics 23, 1019–1032.
Cavanaugh, J.P. (1972). Relation between the immediate memory span and the memory search rate. Psychological Review 79, 525–530.
Chaffin, D.B. See Langolf , Chaffin , and Foulke (1976).
Chapanis, A. , Garner, W.R. , and Morgan, C.T. (1949). Applied Experimental Psychology: Human Factors in Engineering Design. New York: John Wiley and Sons.
Chase, W.G. , and Ericsson, K.A. (1981). Skilled memory. In J.R. Anderson , ed., Cognitive Skills and their Acquisition, Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Chase, W.G. , and Ericsson, K.A. (1982). Skill and Working Memory. Pittsburgh, Pennsylvania: Department of Psychology, Carnegie-Mellon University, Technical Report No. 7; to appear in The Psychology of Learning and Motivation 16, in press.
Chase, W.G. , and Simon, H.A. (1973). Perception in chess. Cognitive Psychology 4, 55–81.
Chase, W.G. See also Akin and Chase (1978); Ericsson , Chase , and Faloon (1980).
Cheatham, P.G. , and White, C.T. (1954). Temporal numerosity: III. Auditory perception of number. Journal of Experimental Psychology 47, 425–428.
Cheng, N.Y. (1929). Retroactive effect and degree of similarity. Journal of Experimental Psychology 12, 444–458.
Chi, M.T. , and Klahr, D. (1975). Span and rate of apprehension in children and adults. Journal of Experimental Child Psychology, 19 434–439.

Chiba, S. See Sakoe and Chiba (1978).
Clark, H.H. , and Clark, E.V. (1976). Psychology and Language: An Introduction to Psycholinguistics. New York: Harcourt, Brace, Jovanovich.
Clark, E.V. See Clark and Clark (1976).
Clark, I.A. See Barnard , Hammond , Morton , Long , and Clark (1981).
Claude, J. (1972). A comparison of five variable weighting procedures. Educational and Psychological Measurement 32, 311–322.
Colatla, V. See Tulving and Colatla (1970).
Conrad, R. (1964). Acoustic confusions in immediate memory. British Journal of Psychology 55, 75–83.
Conway, L. See Mead and Conway (1980).
Coriell, A.S. See Averback and Coriell (1961).
Cornog, J.R. , and Craig, J.C. (1965). Keyboards and coding systems under consideration for use in the sorting of United States mail. 6th Annual Symposium of the IEEE G-HFE, Boston, Massachusetts.
Cornsweet, T.N. (1970). Visual Perception. New York: Academic Press.
Craig, J.C. See Cornog and Craig (1965).
Craik, K.J.W. , and Vince, Margaret A. (1963). Psychological and physiological aspects of control mechanisms. Ergonomics 6, 419–440.
Crossman, E.R.F.W. (1958). Discussion of Paper 7 in National Physical Laboratory Symposium. In Mechanisation of Thought Processes (Vol 2). London: H.M. Stationery Office.
Crossman, E.R.F.W. , and Goodeve, P.J. (1963). Feedback control of hand movements and Fitts' Law. Paper prepared for a meeting of the Experimental Psychology Society, Oxford, July 1963.
Crowder, R.G. (1976). Principles of Learning and Memory. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Crowder, R.G. See also Darwin , Turvey , and Crowder (1972).
Cunitz, Anita R. See Glanzer and Cunitz (1966).
Curtis, B. See Shepard , Curtis , Milliman , and Love (1979).
Daniels, R.W. See Alden , Daniels , and Kanarick (1972).
Dansereau, D. (1968). An Information Processing Model of Mental Multiplication. Ph. D. dissertation, Department of Psychology, Carnegie-Mellon University.
Darwin, C.J. , Turvey, M.T. , and Crowder, R.G. (1972). An auditory analogue of the Sperling partial report procedure: Evidence for brief auditory storage. Cognitive Psychology 3, 255–267.
Deininger, R.L. (1960). Human factors studies of the design and use of push-button telephone keysets. Bell System Technical Journal, 39 995–1012.
De Laurentiis, E.C. (1981). Qualitative Differences in Levels of Performance on a Computer Text-editing Task. M.A. Thesis, Department of Educational Psychology and Counseling, McGill University.
Deutsch, P.L. , and Lampson, B.W. (1967). An online editor. Communications of the ACM 10, 793–803.
Devoe, D.B. (1967). Alternatives to handprinting in the manual entry of data. IEEE Transactions on Human Factors in Electronics HFE-8, 21–31.
DorniC, S. (1977). Attention and Performance VI. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Dornič, S. See also Rabbitt and Dornic (1975).
Dresslar, F.G. (1892). Some influences which affect the rapidity of voluntary movements. American Journal of Psychology 4, 514–527.
Dumais, Susan T. See Shiffrin and Dumais (1981).
Eady, K. (1977). Today's international MTM systems—decision criteria for their use. Proceedings, AIIE 1977 Spring Annual Conference, 483–491.
Eichelman, W.H. See Posner , Boies , Eichelman , and Taylor (1969).
Elkind, J.I. , and Sprague, L.T. (1961). Transmission of information in simple manual control systems. IEEE Transaction on Human Factors in Electronics HFE-2, 58–60.
Embley, D.W. , Lan, M. T. , Leinbaugh, D.W. , and Nagy, G. (1978). A procedure for predicting program editor performance from the user's point of view. International Journal of Man-Machine Studies, 10 639–650.

Embley, D.W. , and Nagy, G. (1981). Behavioral aspects of text editors. Computing Surveys 13, 33–70.
Embley, D.W. See also Anandan , Embley , and Nagy (1980).
Engelbart, D. C. , and English, W.K. (1968). A research center for augmenting human intellect. Proceedings of the 1968 Fall Joint Computer Conference, 395–410. Montvale, New Jersey: AFIPS Press.
Engelbart, D.C. See also English , Engelbart , and Berman (1967).
English, W.K. , Engelbart, D. C. , and Berman, M.L. (1967). Display-selection techniques for text manipulation. IEEE Transactions on Human Factors in Electronics HFE-8, 5–15.
English, W.K. See also Card , English , and Burr (1978); Engelbart and English (1968).
Ericksen, C.W. , and Schultz, D.W. (1978). Temporal factors in visual information processing: A tutorial review. In J. Requin , ed., Attention and Performance VII, Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Ericsson, K.A. , Chase, W. G. , and Faloon, S. (1980). Acquisition of memory skill. Science 208, 1181–1182.
Ericsson, K.A. See also Chase and Ericsson (1981); Chase and Ericsson (1982).
Estes, W. K. , ed. (1975–1978). Handbook of Learning and Cognitive Processes (6 vols). Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Fairbairn, D. G. , and Rowson, J.H. (1978). ICARUS: An interactive integrated circuit layout program. Proceedings of the 15th Annual Design Automation Conference, IEEE, 188–192.
Faloon, S. See Ericsson , Chase , and Faloon (1980).
Feehrer, C.E. See Pew , Baron , Feehrer , and Miller (1977).
Ferrell, W.R. See Sheridan and Ferrell (1974).
Fitter, M. , and Green, T.R.G. (1979). When do diagrams make good computer languages? International Journal of Man-Machine Studies 11, 235–261.
Fitter, M. See also Sime , Fitter , and Green (1975).
Fitts, P.M. (1954). The information capacity of the human motor system in controlling amplitude of movement Journal of Experimental Psychology 47, 381–391.
Fitts, P.M. (1964). Perceptual-motor skill learning. In A.W. Melton , ed., Categories of Human Learning New York: Academic Press.
Fitts, P.M. , and Peterson, J.R. (1964). Information capacity of discrete motor responses. Journal of Experimental Psychology, 67 103–112.
Fitts, P.M. , and Posner, M.I. (1967). Human Performance. Belmont, California: Brooks/Cole.
Fitts, P.M. , and Radford, B. (1966). Information capacity of discrete motor responses under different cognitive sets. Journal of Experimental Psychology 71, 475–482.
Foulke, J.A. See Langolf , Chaffin , and Foulke (1976).
Fox, J.G. , and Stansfield, R.G. (1964). Digram keying times fortypists. Ergonomics 7, 317–320.
Frost, N.H. See Hunt , Frost , and Lunneborg (1973).
Ganz, L. (1975). Temporal factors in visual perception. In E.C. Carterette and M.P. Friedman , eds., Handbook of Perception, Vol. V, Seeing. New York: Academic Press.
Ganz, L. See also Breitmeyer and Ganz (1976).
Gibson, E.J. (1942). Intralist generalization as a factor in verbal learning. Journal of Experimental Psychology 30, 185–200.
Gilbreth, F.B. (1911). Motion Study. New York: D. Van Nostrand.
Gildner, G.G. See Pollack and Gildner (1963).
Glanzer, M. , and Cunitz, Anita R. (1966). Two storage mechanisms in free recall. Journal of Verbal Learning and Verbal Behavior 5, 351–360.
Glanzer, M. , and Razel, M. (1974). The size of the unit in short-term storage. Journal of Verbal Learning and Verbal Behavior, 13 114–131.
Glenn, F.A. See Lane , Strieb , Glenn , and Wherry (1980).
Goodeve, P.J. See Crossman and Goodeve (1963).
Goodwin, Nancy C. (1975). Cursor positioning on an electronic display using lightpen, lightgun, or keyboard for three basic tasks. Human Factors 17, 289–295.
Gould, J. (1968). Visual factors in the design of computer-controlled CRT displays. Human Factors 10, 359–376.
Green, D.M. , and Swets, J.A. (1966). Signal Detection Theory and Psychophysics. Huntington, New York: Robert E. Krieger Publishing Company.

Green, T.R.G. See Sime , Fitter , and Green (1975); Sime and Green (1974) Fitter and Green (1979); Smith and Green (1980).
Guttman, N. , and Julesz, B. (1963). Lower limits of auditory periodicity analysis. Journal of the Acoustical Society of America, 35 610.
Hammer, J.M. (1981). The Human as a Constrained Optimal Text Editor. Ph. D. thesis, Department of Computer Science, University of Illinois. Also Report T-105, Coordinated Science Laboratory, University of Illinois, Urbana, Illinois.
Hammer, J.M. , and Rouse, W.B. (1979). Analysis and modeling of freeform text editing behavior. Proceedings of the 1979 International Conference on Cybernetics and Society, Denver.
Hammond, N.V. See Barnard , Hammond , Morton , Long , and Clark (1981).
Hansen, W.J. (1971). User engineering principles for interactive systems. Proceedings of the Fall Joint Computer Conference 39, 523–532.
Hart, D.J. See Cakir , Hart , and Stewart (1980).
Harter, M.R. (1967). Excitability and cortical scanning: A review of two hypotheses of central intermittency in perception. Psychological Bulletin 68, 47–58.
Harter, N. See Bryan and Harter (1898); Bryan and Harter (1899).
Hatfield, S.A. See Mills and Hatfield (1974).
Hershman, R.L. , and Hillix, W.A. (1965). Data processing in typing, typing rate as a function of kind of material and amount exposed. Human Factors 7, 483–492.
Hick, W.E. (1952). On the rate of gain of information. Quarterly Journal of Experimental Psychology 4, 11–26.
Hillix, W.A. See Hershman and Hillix (1965).
Hirschberg, D.S. (1975). A linear space algorithm for computing maximal common subsequences. Communications of the ACM, 18 341–343.
Hochberg, J. (1976). Toward a speech-plan eye-movement model of reading. In R.A. Monty and J.W. Senders , eds., Eye Movements and Psychological Processes, 397–416, Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Hollan, J.D. See Williams and Hollan (1981).
Hovland, C.I. (1940). Experimental studies in rote learning theory. VI. Comparison of retention following learning to same criterion by massed and distributed practice. Journal of Experimental Psychology 26, 568–587.
Hunt, E.B. , Frost, N.H. , and Lunneborg, C. (1973). Individual differences in cognition: A new approach to intelligence. The Psychology of Learning and Motivation 7, 87–123.
Hyman, R. (1953). Stimulus information as a determinant of reaction time. Journal of Experimental Psychology 45, 188–196.
Ingalls, D.H. (1978). The Smalltalk-76 programming system: Design and implementation. Conference Record of the Fifth Annual ACM Symposium on Principles of Programming Languages, 9–16, Tucson, Arizona.
Johnson, L.M. (1939). The relative effect of a time interval upon learning and retention. Journal of Experimental Psychology 24, 169–179.
Johnson, W.J. (1965). Analysis of Independence of Predetermined Time System Elements. M.S. Thesis, Department of Industrial Engineering, University of Miami.
Julesz, B. See Guttman and Julesz (1963).
Kanarick, A. See Alden , Daniels , and Kanarick (1972).
Karlin, J.E. See Pierce and Karlin (1957).
Kaplan, R.M. , Sheil, B.A. , and Smith, E.R. (1978). Interactive Data-Analysis Language Reference Manual. Palo Alto, California: Xerox Palo Alto Research Center, Technical Report SSL-78-4.
Kay, A. (1977). Microelectronics and the personal computer. Scientific American, September, 230–244.
Keele, S.W. (1968). Movement control in skilled motor performance. Psychological Bulletin 70, 387–403.
Kinkade, R.G. See Van Cott and Kinkade (1972).
Kinkead, R. (1975). Typing speed, keying rates, and optimal keyboard layouts. Proceedings of the 19th Annual Meeting of the Human Factors Society.

Kintsch, W. (1974). The Representation of Meaning in Memory. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Kirshbaum, P.J. See Ramsey , Atwood , and Kirshbaum (1978).
Klahr, D. , and Wallace, J.G. (1976). Cognitive Development: An Information-Processing View. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Klahr, D. See also Chi and Klahr (1975).
Klatzky, R.L. (1980). Human Memory: Structures and Processes, (2nd ed.) San Francisco, California: W.H. Freeman and Company.
Klemmer, E.T. (1962). Communication and human performance. Human Factors 4, 75–79.
Klemmer, E.T. , and Lockhead, G.R. (1962). Productivity and errors in two keying tasks: A field study. Journal of Applied Psychology, 46 401–408.
Kolesnik, P.E. , and Teel, K.S. (1965). A comparison of three manual methods for inputting navigational data. Human Factors 7, 451–456.
Kornblum, S. (1973). Attention and Performance IV. New York: Academic Press.
Kreuger, W.C. (1929). The effect of overlearning on retention. Journal of Experimental Psychology 12, 71–78.
Lampson, B.W. See Deutsch and Lampson (1967).
Lan, M.T. See Embley , Lan , Leinbaugh , and Nagy (1978).
Lane, N. E. , Strieb, M.I. , Glenn, F.A. , and Wherry, R.J. (1980). The Human Operator Simulator: An overview. NATO AGARD Conference on Manned Systems Design: New Methods and Equipment. Frieburg, Federal Republic of Germany.
Landauer, T.K. (1962). Rate of implicit speech. Perception and Psychophysics 15, 646.
Langolf, G.D. (1973). Human Motor Performance in Precise Microscopic Work. Ph. D. Thesis, University of Michigan. Also published by the MTM Association, Fairlawn, New Jersey, 1973.
Langolf, G.D. , Chaffin, D.B. , and Foulke, J.A. (1976). An investigation of Fitts's Law using a wide range of movement amplitudes. Journal of Motor Behavior 8, 113–128.
Leinbaugh, D.W. See Embley , Lan , Leinbaugh , and Nagy (1978).
Lester, O.P. (1932). Mental set in relation to retroactive inhibition. Journal of Experimental Psychology 15, 681–699.
Lindsay, P.H. , and Norman, D.A. (1977). Human Information Processing: An Introduction to Psychology (2nd ed.). New York: Academic Press.
Lockhead, G.R. See Klemmer and Lockhead (1962).
Loftus, E.F. (1979). Eyewitness Testimony. Cambridge, Massachusetts: Harvard University Press.
Long, J.B. (1976). Visual feedback and skilled keying: Differential effects of masking the printed copy and the keyboard. Ergonomics 19, 93–110.
Long, J.B. , and Baddeley, A. , eds. (1981). Attention and Performance IX. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Long, J.B. See also Barnard , Hammond , Morton , Long , and Clark (1981).
Love, T. See Shepard , Curtis , Milliman , and Love (1979).
Luh, C.W. (1922). The conditions of retention. Psychological Monographs 31, No. 3 (Whole No. 142).
Lunneborg, C. See Hunt , Frost , and Lunneborg (1973).
Martin, J. (1973). Design of Man-Computer Dialogues. Englewood Cliffs, New Jersey: Prentice-Hall.
Margolius, G. See Weiss , and Margolius (1954).
Massaro, D.W. (1970). Preperceptual auditory images. Journal of Experimental Psychology 85, 411–417.
Maynard, H.B. (1971). Industrial Engineering Handbook, 3rd ed. New York: McGraw-Hill.
Mayzner, M.S. , and Tresselt, M.E. (1965). Tables of single-letter and digram frequency counts for various word-length and letter-position combinations. Psychonomic Monograph Supplements 1, 13–32.
McCormick, E.J. (1976). Human Factors in Engineering and Design. New York: McGraw-Hill.
Mead, C. , and Conway, L. (1980). Introduction to VLSI Systems. Reading, Massachusetts: Addison-Wessley.
Meister, D. (1976). Behavioral Foundations of System Development. New York: John Wiley and Sons.

Melton, A. (1963). Implications of short-term memory for a general theory of memory. Journal of Verbal Learning and Verbal Behavior 2, 1–21.
Michotte, A. (1946/1963). The Perception of Causality. New York: Basic Books, 1963. Originally published as La Perception de la Causalité. Louvain: Publications Universitaires de Louvain, 1946.
Michon, J.A. (1978). The making of the present: A tutorial review. In J. Requin , ed., Attention and Performance VII, 89–111, Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Miller, G.A. (1956). The magical number seven plus or minus two: Some limits on our capacity for processing information. Psychological Review 63, 81–97.
Miller, L.A. , and Thomas Jr., J.C. , (1977). Behavioral issues in the use of interactive systems. International Journal of Man-Machine Studies 9, 509–536.
Miller, D.C. See Pew , Baron , Feehrer , and Miller (1977).
Milliman, D. See Shepard , Curtis , Milliman , and Love (1979).
Mills, R.G. , and Hatfield, S.A. (1974). Sequential task performance, task module relationships, reliabilities, and times. Human Factors 16, 117–128.
Minor, F.J. , and Pittman, G.G. (1965). Evaluation of variable format entry terminals for a hospital information system. Paper presented at the Sixth Annual Symposium of the IEEE Professional Group on Human Factors in Electronics, Boston.
Minor, F.J. , and Revesman, S.L. (1962). Evaluation of input devices for a data setting task. Journal of Applied Psychology 46, 332–336.
Moran, T.P. (1980). Compiling Cognitive Skill. AIP Memo 150, Xerox Palo Alto Research Center.
Moran, T.P. (1981a). The Command Language Grammar: A representation for the user interface of interactive computer systems. International Journal of Man-Machine Systems 15, 3–50.
Moran, T.P. , ed. (1981b). Special Issue: The Psychology of Human-Computer Interaction. Computing Surveys 13, March.
Moran, T.P. , and Card, S.K. (1982). Applying Cognitive Psychology to Computer Systems. Proceedings of the Conference on Human Factors in Computer Systems, Gaithersburg, Maryland.
Moran, T.P. See also Card , Moran , and Newell (1976, 1980a, 1980b); Roberts and Moran (1982).
Morton, J. See Barnard , Hammond , Morton , Long , and Clark (1981).
Munger, S.J. , Smith, R.W. , and Payne, D. (1962). An Index of Electronic Equipment Operability. Pittsburgh, Pennsylvania: American Institute for Research, Report AIR-C43-l/62-RP(1).
Murdock, B.B., Jr. (1960b). The immediate retention of unrelated words. Journal of Experimental Psychology 60, 222–234.
Murdock, B.B., Jr. (1961). Short-term retention of single paired-associates. Psychological Reports 8, 280.
Murdock, B.B., Jr. (1963). Short-term retention of single paired associates. Journal of Experimental Psychology 65, 433–443.
Murdock, B.B., Jr. (1967). Recent developments in short-term memory. British Journal of Psychology 58, 421–433.
Murdock, B.B., Jr. (1974). Human Memory: Theory and Data. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Myer, T.H. , and Barnaby, J.R. (1973). TENEX executive language manual for users. Cambridge, Massachusetts: Bolt, Beranek, and Newman, Inc.
Nagy, G. See Embley , Lan , Leinbaugh , and Nagy (1978); Anandan , Embley , and Nagy (1980); Embley and Nagy (1981).
Nanda, R. (1968). The additivity of elemental times. Journal of Industrial Engineering 19(5), 235–242.
Neal, A.S. (1977). Time intervals between keystrokes, records, and fields in data entry with skilled operators. Human Factors 19, 163–170.
Neisser, U. (1967). Cognitive Psychology. New York: Appleton-Century-Crofts.
Newell, A. (1973). Production systems: Models of control structures. In W.G. Chase , ed., Visual Information Processing, 283–308, New York: Academic Press.

Newell, A. (1980). Reasoning, problem solving, and decision processes: The problem space as a fundamental category. In R. Nickerson , ed., Attention and Performance VIII, Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Newell, A. , and Rosenbloom, P.S. (1981). Mechanisms of skill acquisition and the law of practice. In J.R. Anderson , ed., Cognitive Skills and their Acquisition, 1–51, Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Newell, A. , and Simon, H.A. (1972). Human Problem Solving. Englewood Cliffs, New Jersey: Prentice-Hall.
Newell, A. See also Card , Moran , and Newell (1976, 1980a, 1980b); Siewiorek , Bell , and Newell (1981).
Newman, W. , and Sproull, R. (1979). Principles of Interactive Computer Graphics, 2nd ed. New York: McGraw-Hill.
Nilsson, N. (1971). Problem-Solving Methods in Artificial Intelligence. New York: McGraw-Hill.
Norman, D.A. (1980). Cognitive engineering and education. In D.T. Tuma , and F. Reif , eds., Problem Solving in Education: Issues in Teaching and Research, 97–107, Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Norman, D.A. (1981). Categorization of action slips. Psychological Review 88, 1–15.
Norman, D.A. , and Bobrow, D. (1975). On data-limited and resource-limited processes. Cognitive Psychology 7, 44–64.
Norman, D.A. , and Rumelhart, D.E. (1975). Explorations in Cognition. San Francisco: W.H. Freeman.
Norman, D.A. See also Waugh and Norman (1965); Lindsay and Norman (1977).
Oren, S.S. (1972). A mathematical model for computer-assisted document creation. Proceedings of the Fourth International Symposium on Computer and Information Sciences, Miami Beach, Florida.
Oren, S.S. (1974). A mathematical theory of man-machine text editing. IEEE Transactions on Systems, Man, and Cybernetics SMC-4, 256–267.
Oren, S.S. (1975). A mathematical theory of man-machine document assembly. IEEE Transactions on Systems, Man, and Cybernetics SMC-5, 256–267.
Parsons, H.M. (1972). Man-Machine Systems Experiments. Baltimore, Maryland: Johns Hopkins University Press.
Payne, D. See Munger , Smith , and Payne (1962).
Peterson, J.R. See Fitts and Peterson (1964).
Peterson, L.R. , and Peterson, M.J. (1959). Short-term retention of individual verbal items. Journal of Experimental Psychology, 58 193–198.
Peterson, M.J. See Peterson and Peterson (1959).
Pew, R.W. , Baron, S. , Feehrer, C.E. , and Miller, D.C. (1977). Critical Review and Analysis of Performance Models Applicable to Man-Machine Systems Evaluation. Cambridge, Massachusetts: Bolt, Beranek, and Newman, Inc., Report 3446.
Pierce, J.R. , and Karlin, J.E. (1957). Reading rates and the information rate of the human channel. Bell System Technical Journal 36, 497–516.
Pittman, G.G. See Minor and Pittman (1965).
Pollack, W.T. , and Gildner, G.G. (1963). Study of Computer Manual Input Devices. Hanscom Field, Bedford, Massachusetts: Air Force Systems Command, Electronic Systems Division, September, Report ESD-TDR-63-545.
Posner, M.I. (1978). Chronometric Explorations of Mind. Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Posner, M.I. , Boies, S.J. , Eichelman, W.H. , and Taylor, R.L. (1969). Retention of visual and name codes of single letters. Journal of Experimental Psychology 79, 1–16.
Posner, M.I. See also Fitts and Posner (1967).
Poulton, E.C. (1974). Tracking Skill and Manual Control. New York: Academic Press.
Quick, J.H. (1962). Work Factor Time Standards. New York: McGraw-Hill.
Rabbitt, P.M.A. , and Dornič, S. (1975). Attention and Performance V. London: Academic Press.
Radford, B. See Fitts and Radford (1966).
Ramsey, H.R. , and Atwood, M.E. (1979). Human Factors in Computer Systems: A Review of the Literature. Englewood, Colorado: Science Applications, Inc., Technical Report SAI-79-111-DEN, NTIS AD A075679.

Ramsey, H.R. , Atwood, M.E. , and Kirshbaum, P.J. (1978). A Critically Annotated Bibliography of the Literature on Human Factors in Computer Systems. Englewood, Colorado: Science Applications, Inc., Technical Report SAI-78-070-DEN, NTIS AD-A057081.

Raphael, B. See Bobrow and Raphael (1974).

Raymond, B. (1969). Short-term storage and long-term storage in free recall. Journal of Verbal Learning and Verbal Behavior 8, 567–574.

Razel, M. See Glanzer and Razel (1974).

Reed, S.K. See Simon and Reed (1976).

Reisner, Phyllis (1981). Using a formal grammar in human factors design of an interactive graphics system. IEEE Transactions on Software Engineering SE-7, 229–240.

Requin, J. (1978). Attention and Performance VII. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Revesman, S.L. See Minor and Revesman (1962).

Rice, D.E. See Van Dam and Rice (1971).

Richardson, J. See Underwood and Richardson (1956).

Riddle, Elizabeth A. (1976). Comparative Study of Various Text Editors and Formatting Systems. Washington, D.C.: Air Force Data Services Center, The Pentagon, AD-A029 050.

Roberts, Teresa L. (1979). Evaluation of Computer Text Editors. Ph. D. Thesis, Department of Computer Science, Stanford University. Reprinted as Xerox Palo Alto Research Center Technical Report SSL-79-9.

Roberts, Teresa L. , and Moran, T.P. (1982). A methodology for evaluating text editors. Proceedings of the Conference on Human Factors in Computer Systems, Gaithersburg, Maryland.

Rosenbloom, P.S. See Newell and Rosenbloom (1981).

Rouse, W.B. (1977). Human-computer interaction in multi-task situations. IEEE Transactions on Systems, Man, and Cybernetics SMC-7, 384–392.

Rouse, W.B. (1980). Systems Engineering Models of Human-Machine Interaction. New York: North Holland.

Rouse, W.B. See also Hammer and Rouse (1979).

Rowson, J.H. See Fairbaim and Rowson (1978).

Rumelhart, D.E. See Norman and Rumelhart (1975).

Russell, D.S. (1973). Poet: A Page Oriented Editor for Tenex. Computer Science Division, University of Utah.

Russo, J.E. (1978). Adaptation of cognitive processes to the eye-movement system. In J.W. Senders , D.F. Fisher , and R.A. Monty , eds., Eye Movements and the Higher Psychological Functions, 89–109. Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Sackman, H. (1970). Experimental analysis of man-computer problemsolving. Human Factors 12, 187–201.

Sakoe, H. , and Chiba, S. (1978). Dynamic programming algorithm optimization for spoken word recognition. IEEE Transactions on Acoustics, Speech, and Signal Processing ASSP-26, 43–49.

Savitsky, S. (1969). Son of Stopgap. Stanford, California: Stanford University Artificial Intelligence Laboratory, Operating Note 50. 1.

Schmidtke, H. , and Stier, F. (1961). An experimental evaluation of the. validity of predetermined elemental time systems. The Journal of Industrial Engineering XII (3), 182–204.

Schneider, W. See Shiffrin and Schneider (1977).

Schultz, D.W. See Ericksen and Schultz (1978).

Schulz, R.W. See Underwood and Schulz (1960).

Seibel, R. (1964). Data entry through chord, parallel entry devices. Human Factors 6, 189–192.

Seibel, R. (1972). Data entry devices and procedures. In H.P. VanCott and R.G. Kinkade , eds., Human Engineering Guide to Equipment Design, Washington, D.C.: U.S. Government Printing Office.

Sheil, B. (1981). The psychological study of programming. Computing Surveys 13, 101–120.

Sheil, B.A. See also Kaplan , Sheil , and Smith (1968).

Shepard, S. , Curtis, B. , Milliman, P. , and Love, T. (1979). Modern coding practices and programmer performance. Computer 12, 41–49.

Sheridan, T.B. , and Ferrell, W.R. (1974). Man-machine systems: Information, control, and decision models of human performance. Cambridge, Massachusetts: M.I.T. Press.

Shiffrin, R.M. and Dumais, Susan T. (1981). The development of automatism. In J.R. Anderson , ed., Cognitive Skills and their Acquisition, 111–140, Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Shiffrin, R.M. , and Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. Psychological Review 84, 127–190.

Shiffrin, R.M. See also Atkinson and Shiffrin (1968).

Shneiderman, B. (1980). Software Psychology. Cambridge, Massachusetts: Winthrop.

Shurtleff, D.A. (1980). How to Make Displays Legible. La Mirada, California: Human Interface Design.

Siegal, A.I. , and Wolf, J.J. (1969). Man-machine simulation models. New York: John Wiley and Sons.

Siewiorek, D. , Bell, G. , And Newell, A. (1981). Computer Structures. New York: McGraw-Hill.

Sime, M.E. , Fitter, M. , and Green, T.R.G. (1975). Why is programming computers so hard? New Behaviour (September 4).

Sime, M.E. , and Green, T.R.G. (1974). Psychology and the Syntax of Programming. Medical Research Council, Social and Applied Psychology Unit, Department of Psychology, The University, Sheffield, MRC Memo No. 52.

Simon, H.A. (1947). Administrative Behavior. New York: Macmillan.

Simon, H.A. (1969). The Sciences of the Artificial. Cambridge, Massachusetts: M.I.T. Press.

Simo, H.A. (1974). How big is a chunk? Science 183, 482–488.

Simon, H.A. (1975). The functional equivalence of problem solving skills. Cognitive Psychology 7, 268–288.

Simon, H.A. See also Newell and Simon (1972); Chase and Simon (1973).

Smith, E.R. See also Kaplan , Sheil , and Smith (1978).

Smith, G.A. (1977). Studies of compatibility and a new model of choice reaction time. In S. Domič , ed., Attention and Performance VI, Hillsdale, New Jersey: Lawrence Erlbaum Associates.

Smith, H.T. , and Green, T.R.G. , eds. (1980). Human Interaction with Computers. London: Academic Press.

Smith, R.W. See also Munger , Smith , and Payne (1962).

Snoddy, G.S. (1926). Learning and stability. Journal of Applied Psychology 10.

Sperandio, J.C. , and Bisseret, A. (1974). Human Factors in the Study of Information Input Devices. Royal Aircraft Establishment Library Translation No. 1728. Originally published as Facteurs humains dans l’étude des dispositifs d’entrée d’informations, Bulletin du CERP 17, 4, 269–294 (1968).

Sperling, G. (1960). The information available in brief visual presentations. Psychological Monographs 74 (11, Whole No. 498).

Sperling, G. (1963). A model for visual memory tasks. Human Factors 5, 19–31.

Sprague, L.T. See Elkind and Sprague (1961).

Sproull, R. See Newman and Sproull (1979).

Stallman, R.M. (1981). EMACS—The extensible, customizable self-documenting display editor. Proceedings of the ACM SIGPLAN SIGOA Symposium on Text Manipulation, Portland, Oregon, 147–156.

Stanford Center For Information Processing (1975). Wylbur/ 370—the Stanford Timesharing System—Reference Manual, 3rd ed. Stanford, California: Stanford University.

Sternberg, S. (1975). Memory scanning: New findings and current controversies. Quarterly Journal of Experimental Psychology, 27 I–32.

Stewart, T.F.M. See Cakir , Hart , and Stewart (1980).

Stier, F. See Schmidtke and Stier (1961).

Strieb, M.I. See Lane , Strieb , Glenn , and Wherry (1980).

Swets, J.A. See Green and Swets (1966).

Taylor, R.C. See Posner , Boies , Eichelman , and Taylor (1969).

Teel, K.S. See Kolesnik and Teel (1965).

Teitelman, W. (1978). INTERLISP Reference Manual. Palo Alto, California: Xerox Palo Alto Research Center.

Thompson, D.M. See Tulving and Thompson (1973).
Thomas, J.C., Jr. See Miller and Thomas (1977).
Tresselt, M.E. See Mayzner and Tresselt (1965).
Tulving, E. , and Colatla, V. (1970). Free recall of trilingual lists. Cognitive Psychology 1, 86–98.
Tulving, E. , and Thompson, D.M. (1973). Encoding specificity and retrieval processes in episodic memory. Psychological Review 80, 352–373.
Turvey, M.T. See Darwin , Turvey , and Crowder (1972).
Tversky, A. (1977). Features of similarity. Psychological Review 84, 327–352.
Underwood, B.J. (1952). Studies of distributed practice: VII. Learning and retention of serial nonsense lists as a function of intralist similarity. Journal of Experimental Psychology 44, 80–87.
Underwood, B.J. (1953a). Studies of distributed practice: VIII. Learning and retention of paired nonsense syllables as a function of intralist similarity. Journal of Experimental Psychology 45, 133–142.
Underwood, B.J. (1953b). Studies of distributed practice: IX. Learning and retention of paired adjectives as a function of intralist similarity. Journal of Experimental Psychology 45, 143–149.
Underwood, B.J. (1953c). Studies of distributed practice: X. The influence of intralist similarity on learning and retention of serial adjective lists. Journal of Experimental Psychology 45, 253–259.
Underwood, B.J. (1957). Interference and forgetting. Psychological Review 64, 49–60.
Underwood, B.J. , and Richardson, J. (1956). The influence of meaningfulness, intralist similarity, and serial position on retention. Journal of Experimental Psychology 52, 119–126.
Underwood, B.J. , and Schulz, R.W. (1960). Meaningfulness and Verbal Learning Philadelphia: Lippincott.
Vallee, J. (1976). There ain't no user science: a tongue-in-cheek discussion of interactive systems. Proceedings of the American Society for Information Science Annual Meeting 13, San Francisco.
Van Cott, H.P. , and Kinkade, R.G. (1972). Human Engineering Guide to Equipment Design (revised ed.). Washington, D.C.: U.S. Government Printing Office.
Van Dam, A. , and Rice, D.E. (1971). On-line text editing: A survey. Computing Surveys 3, 93–114.
VanLehn, K. See Brown and VanLehn (1980).
Vince, Margaret A. (1948). Corrective movements in a pursuit task. Quarterly Journal of Experimental Psychology 1, 85–103.
Vince, Margaret A. See also Craik and Vince (1963).
Wainer, H. (1976). Estimating coefficients in linear models: It don't make no nevermind. Psychological Bulletin 83, 213–217.
Wallace, J.G. See Klahr and Wallace (1976).
Waugh, N.C. , and Norman, D. A. (1965). Primary memory. Psychological Review 72, 89–104.
Weiss, W. , and Margolius, G. (1954). The effect of context stimuli on learning and retention. Journal of Experimental Psychology, 48 318–322.
Welford, A.T. (1968). Fundamentals of SkilL London: Methuen.
Welford, A.T. (1973). Attention, strategy and reaction time: A tentative metric. In S. Komblum , ed., Attention and Performance IV, 37–54. New York: Academic Press.
Wherry, R.J. See Lane , Strieb , Glenn , and Wherry (1980).
White, C.T. See Cheatham and White (1954).
Wicklegren, W.A. (1977). Learning and Memory. Englewood Cliffs, New Jersey: Prentice-Hall.
Wicklegren, W.A. (1981). Human learning and memory. Annual Psychology Review 32, 21–52.
Williams, M. (1950). The effects of experimental induced needs on retention. Journal of Experimental Psychology 40, 139–126.
Williams, M.D. , and Hollan, J.D. (1981). The process of retrieval from very long term memory. Cognitive Science 5, 87–119.
Wolf, J.J. See Siegel and Wolf (1969).
Yamada, H. (1980a). A historical study of typewriters and typing methods: From the position of planning Japanese parallels. Journal of Information Processing 2, 179–202.
Yamada, H. (1980b). An analysis of the standard English keyboard. Department of Information Science, Faculty of Science, University of Tokyo, Technical Report 80-11.

Young, R.M. (1976). Seriation by Children: An Artificial Intelligence Analysis of a Piagetian Task. Basel: Birkhauser.
Young, R.M. (1981). The machine inside the machine: User’s models of pocket calculators. International Journal of Man-Machine Systems 15, 51–86.
Youtz, A.C. (1941). An experimental evaluation of Jost’s laws. Psychological Monographs 53, No. 1 (Whole No. 238).