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# SESSION I
# PRESIDENTIAL ADDRESS

# The computer as a metaphor for psychological inquiry: Considerations and recommendations

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My concern is with the computer as a metaphor for explaining perception and action. A representative sample of arguments for and against the paradigm are presented and evaluated. The conclusion is that the idea of computation is productive for achieving a functionalist description of how we perceive and act. This level of description can contribute to our understanding independently of description achieved at the levels of neurophysiology and phenomenology. Some of the perceived limitations in the computational method rest on the assumption that the symbolic level must be discrete and abstract. In fact, worthwhile explanations within the information processing framework utilize continuous, modality-specific processes and representations as explanatory devices. One suggestion for a movement from the discrete to the continuous mode is advised to bring computational theories in line with the psychological phenomena they describe. Various alternatives to the computational framework are considered and found to be inadequate substitutes. An example of research is used to demonstrate the value of the continuous mode and the computational level of explanation.

My view of scientific development is represented by Stephen Toulmin's (1972) model of continuous and gradual accumulation and by Thomas Kuhn's (1962) idea of a paradigm shift. Scientists stand on the shoulders of their ancestors and colleagues; presidential addresses should be no different. Last year, Geoffrey Loftus (1985) began his Presidential Address to members of this Society by acknowledging the value of computers in scientific endeavors, as illustrated by the excellent summary provided by Russell Church (1983) in his Presidential Address two years earlier. The important caveat was that computer simulation models might distract us from the more important goal of finding simple laws. Loftus illustrated his message very nicely by imbuing Johannes Kepler with current simulation capabilities. In this fantasy, Kepler could simply have chosen to add a few more free epicycles (free parameters) in an incorrect Copernican model, rather than laboriously working out his simple laws of planetary motion. I believe that Loftus touched on worthwhile considerations that go far beyond computer simulation. A remarkable number of issues have become apparent, such as the nature of theory and explanation, the target phenomena for theory, and the appropriate levels of explanation in psychological inquiry. My goal is to touch upon these issues while addressing the question of the value of the computer as a metaphor for psychological inquiry. In this manner, I am able to provide continuity with previous addresses while simultaneously being faithful to the organization's concern with computers in psychology.

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## MIND-BODY PROBLEM

Psychology has its roots in philosophy and physiology; at a fundamental level, the computer metaphor represents a solution to the mind-body problem. Psychology investigates empirically not only the behavioral and mental worlds, but the relation between the two. If the science succeeds, one outcome will be a solution to the mind-body problem. Until it does, however, we can dabble in metaphysics and speculate on how the script will be written. In fairness to our philosophically minded ancestors, and as a background for current endeavor, Figure 1 shows graphic representations of six solutions to the mind-body problem, or, as illustrated, the ghost-machine problem.

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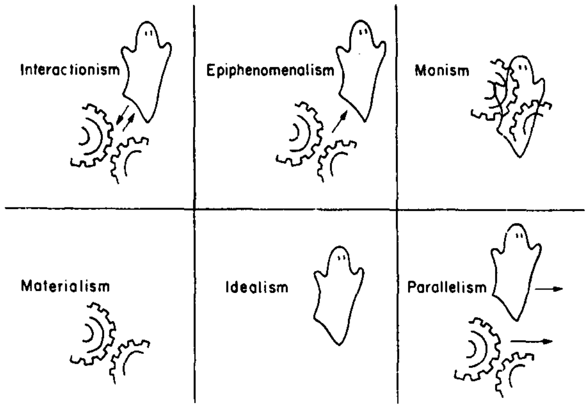


**Figure 1. Graphic representations of six solutions to the mind-body problem.**

Descartes (Figure 2) accepted the dichotomy of mind and body bequeathed by Plato, but linked the operations of the two in a form of interactionism. Two different things, mind and body, communicate to produce a phenomenal impression of the "I" interacting with the body. Being contrary, perhaps, Leibniz proposed parallelism or an independence of mind and body. Any apparent coincidence reflects only the harmony established by God. Epiphenomenalism claims that mental processes are nothing more than the by-product of the physical body. These processes have no consequences of their own. Materialism, the foundation of behaviorism, denies the existence of mental processes altogether. Tit for tat, idealism denies body rather than mind. Monism, my favorite solution and the one most consistent with the computer metaphor, posits that the physical properties of humans (and other animals) embody the attributes of mental processes. Like a computer, a purely physical system exhibits "intelligent" functioning between input and output. Although mental processes are tied to physical systems, one cannot be completely reduced to the other. Mental processes exist and influence observable behavior; any complete explanation of behavior will include a level of description encompassing these processes.

**Figure 2. Rène Descartes, 1596–1650.**

## A BRIEF HISTORY OF COMPUTATION

Mechanical computers antedated computers as we know them (Williams, 1978a, 1978b). Figure 3 shows a bird organ, a mechanical device that produced a very close simulation of a bird's song. A couple of centuries ago, no parlor would have been without one, if its expensive price tag were within the family's means. The best-known automaton is Jacques de Vaucanson's mechanical duck, shown in Figure 4. This creature, built in the middle of the 18th century, is best summarized by the following account:

**Figure 3. A bird organ which produced a simulation of a bird's song.**

> After a light touch on a point on the base, the duck in the most natural way in the world begins to look around him,

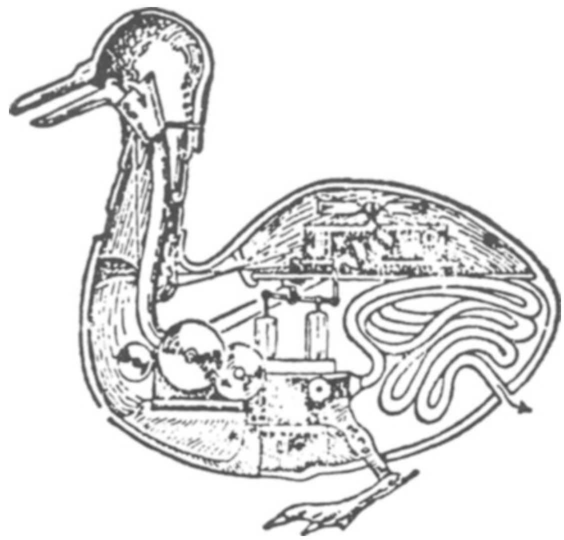

**Figure 4. A depiction of de Vaucanson's mechanical duck (see text for a description).**

**Figure 5. An etching of an exhibition of automata held in London in 1836.**

eyeing the audience with an intelligent air. His lord and master, however, apparently interprets this differently, for soon he goes off to look for something for the bird to eat. No sooner has he filled a dish with oatmeal porridge than our famished friend plunges his beak deep into it, showing his satisfaction by some characteristic movements of his tail. The way in which he takes the porridge and swallows it greedily is extraordinarily true to life. In next to no time the basin has been half emptied, although on several occasions the bird, as if alarmed by some unfamiliar noises, has raised his head and glanced curiously around him.

After this, satisfied with his frugal meal, he stands up and begins to flap his wings and to stretch himself while expressing his gratitude by several contented quacks. But most astonishing of all are the contractions of the bird's body clearly showing that his stomach is a little upset by this rapid meal and the effects of a painful digestion become obvious. However, the brave bird holds out, and after a few moments we are convinced in the most concrete manner that he has overcome his internal difficulties. The truth is that the smell which now spreads through the room becomes almost unbearable. We wish to express to the artist inventor the pleasure which his demonstration gave to us. (Chapuis & Droz, 1958, quoted in Williams, 1978a, pp. 56-57)

Vaucanson's automaton had the necessary property of synchronous control of multiple functions, a behavioral property that psychologists have yet to illuminate.

Automata were the rage in the 19th century, as can be seen in Figure 5, which shows an etching of an exhibition held in London in 1836. This gathering seems to bear some similarity to our computer trade fairs, or even possibly to our Computers in Psychology meetings.

Surprisingly, it is difficult to find some record of automatous speaking machines' being available before the beginning of the 20th century. Figure 6 shows a drawing of Joseph Faber's speech organ and the human operator. The performance held in London in 1846 consisted of ordinary and whispered speech and the singing of airs, ending with "God Save the Queen" (Victoria). Maybe speech was believed to be special even in those times. Other remarkable mechanical devices existed. On the writing side, the Maillardet automaton constructed 200 years ago (see Figure 7) could both write and draw. An example of its writing with a ballpoint pen is shown in Figure 8.

Calculation and storage of numbers is fundamental to the concept of computation. The representation of numbers is important for what computation is feasible. Roman numerals and Chinese notation do not permit a manageable method of multiplication. Arabic numerals make multiplication reasonable but tedious and involved. The Scotsman John Napier invented logarithms to simplify multiplication and division. Logarithms might be considered a machine language. The inputs of interest are translated (transformed) before computation and translated back again into the standard notation after computation is complete. The instantiation of logarithms by lengths on a scale or ruler was, of course, the slide rule which

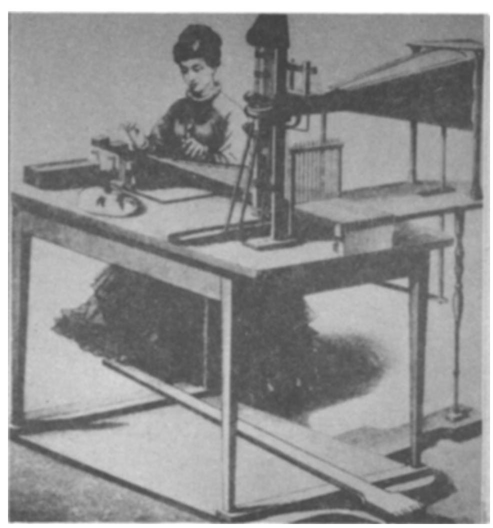

**Figure 6. Joseph Faber's speech organ (see text for description) From "The speaking machine of Wolfgang von Kempelen" by H. Dudley and T. H. Tarnoczy, 1950, *Journal of the Acoustical Society of America*, 22. Reprinted by permission of publisher.**

**Figure 7. The Maillardet automaton that could both write and draw.**

hung by the sides of science and engineering students. These were replaced by small hand calculators only a decade or so ago.

Blaise Pascal (Figure 9) designed a mechanical calculator to help his father, a tax collector, carry out his burdensome financial calculations. The calculator was similar in many respects to a speedometer on a car, with interlocking cogs and wheels on rotating axles (Trask, 1971). Gottfried Wilhelm Leibniz (Figure 10) made multiplication and division much easier by separating the teeth on the multiplying wheel by different lengths. Wang calculators, found in every psychology statistics laboratory until just a few decades ago, were basically of a Pascaline design, with Leibniz's modification, but were powered by electricity rather than by hand.

Figures 11 and 12 present portraits of two of the best-known figures in the history of computation. Charles Babbage's second-generation calculator, the analytical engine, is acknowledged as the first programmable computer. It had input and output devices, a processor and a memory store, and a control unit. The input was modelled after an invention of Joseph Jacquard, used for the weaving of cloth. A stiff card with a series of holes would guide the appropriate threads into the loom, controlling exactly the pattern of the weave. Ada Augusta, Countess of Lovelace and daughter of Lord Byron, contributed to the project by documenting the enterprise and evaluating it positively at a mathematical level. She also anticipated the issue of whether or not the computer can do more than it was programmed to do. She answered negatively (Evans, 1979).

George Boole (Figure 13), the progenitor of information theory, provided the theory of logic to breathe life into the machines of Pascal, Leibniz, and Babbage. Alan Turing proved mathematically what Babbage had believed: that a single machine could compute any set of mathematical operations, and hence the general-purpose computer was mathematically feasible. It is interesting that the developments of Boole and Turing with respect to logic, design, and function were independent of hardware implementation. The latter had its own chain of progress and the two parallel developments support the qualitative distinction between software (algorithm) and hardware (instantiation) levels of implementation and understanding.

Konrad Zuse (Figure 14) claimed that he had no knowledge of Babbage's analytical engine when he conceptualized extending the principles of a special-purpose calculator to one that could perform any mathematical task (Evans, 1979). The implementation, he believed, should be in binary rather than decimal calculation units, and he proceeded to build a working model using Erector-set parts and cheap off-the-shelf components. In the successive generations of models, the hardware, but not the design, changed again, illustrating again the relative independence of these two levels.

The Americans, led by Mauchly and Eckert, proposed and built a general-purpose ENIAC (Electronic Numerical Integrator and Calculator) (McCorduck, 1979). Although the machine was programmable in principle, one had to rewire part of the machine to switch from one kind of programming task to another. It was the mathematician John von Neumann (Figure 15) who suggested the design advance that programs should be stored in the machine in the same manner as the information to be calculated. This insight, and the progressive miniaturization brought about by developments in microelectronics, has generated, after just three decades, supercomputers executing billions of operations per second with memories of $10^{10}$ bits, and computers in a briefcase for just a few million lira. Perhaps part of the attraction of the computer

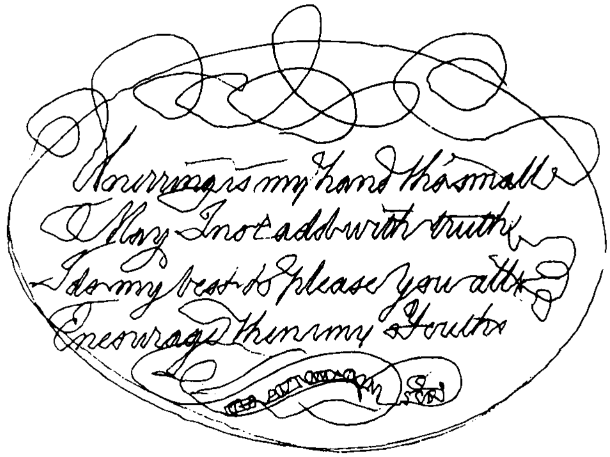

**Figure 8. An example of the writing produced by the Maillardet automaton.**

**Figure 9. Gabriel (Blaise) Pascal, 1623–1662.**

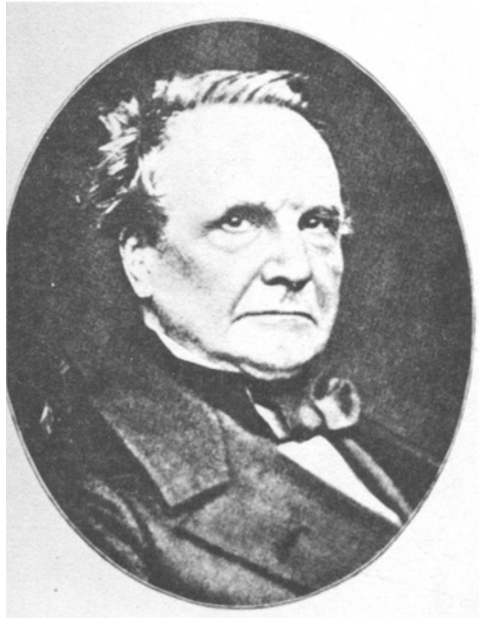

**Figure 11. Charles Babbage, 1791–1871.**

**Figure 10. Gottfried Wilhelm Leibniz, 1646–1716.**

**Figure 12. Ada Augusta, Countess of Lovelace, 1815–1851.**

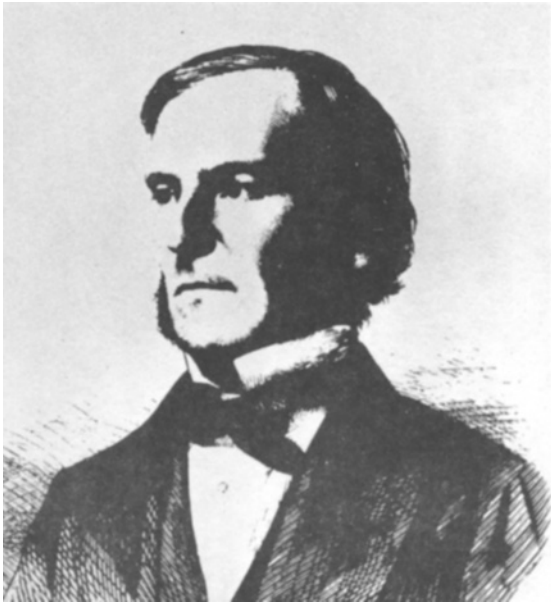

Figure 13. George Boole, 1815–1864.

Figure 15. John von Neumann, 1903-1957.

Figure 14. Konrad Zuse, 1910.

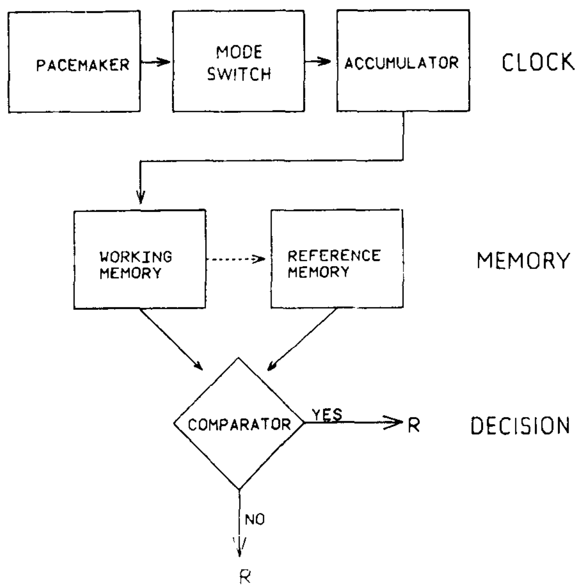


Figure 16. An information-processing model of timing (after Church, 1983).

as a metaphor for psychology is that some of this progress might be contagious.

## THE COMPUTATIONAL MODEL

Church's (1983) exposition on the value of computers began with its serving as a model of intelligent behavior. None of us found this very surprising, since the computer metaphor has been around long enough that most of you were weaned on it. This analogy between man and machine has extended well beyond the boundaries of psychology and cognitive science, and the computer age has important implications for social sciences. I will have nothing to say about this, but I recommend the emerging literature exploring the implications for modern individual, social, and political consciousness (Edwards, 1984; Evans, 1979; Pohl & Shaw, 1981, Chap. 10). To tweak your interest, there are intriguing questions such as (1) the contribution of cybernetics to military technology and our attitudes to power and war, (2) the socialization of individuals who now have the option of replacing many common social interactions with computer interactions, and (3) whether an intelligent electronic garbage compactor with decision-making and speaking skills should have inalienable rights.

Figure 16 gives the information-processing model of timing used by Church to illustrate the computer-like properties of the model. All of us are familiar with the components of switches, accumulators, memories, and comparators by way of both our computers and our models. It wasn't always this way. It was only about four decades ago that our primitive concept of scientific explanation changed from energy to information. Wiener's *Cybernetics* (1948) and Shannon's (1948) papers (see Figures 17 and 18) can be considered landmarks for replacing the Newtonian concept of energy with the concept of information. The concepts of information theory, including coding, storage, number of alternatives, and noise, appeared to provide more meaningful explanations of both electronic machines and human behavior. George Miller (1953) (see Figure 19) informed the psychological community about these developments; he had found them highly valuable in describing language and communication (Miller, 1951). [Three decades later, Miller's orientation to language appears to be dominated by biological rather than informational explanations (see Miller, 1981).] Gentner and Grudin (1985) documented what we already knew by finding a progression of more systematic, explicit metaphors during psychology's century of history. The convergence on systems metaphors must be attributed to (or blamed on) the information revolution.

Figure 17. Norbert Wiener.

**Figure 18. Claude Shannon. Photograph printed with permission of CW Communications, Boston, MA.**

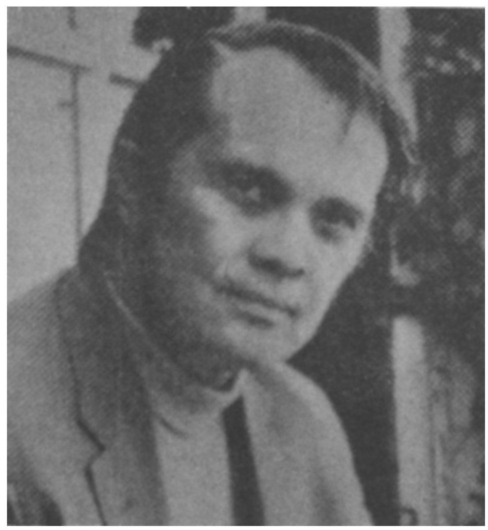

**Figure 19. George A. Miller. Photographed printed with permission of George A. Miller.**

The computational or information-processing approach ascribes internal states and processes to explain and understand much of behavior. The states are informationbearing states (see Dretske, 1981), and the processes transform information (Neisser, 1967). Dretske (1985) provides a recent example of utilizing the information-processing level to explain behavior. Consider a rat in a Skinner box, trained to press the lever for a food reward only during the appearance of a triangle. The past experience of the rat establishes a meaning relationship between the triangle and the outcome of pressing the lever. Some internal representation can be considered to be causally involved in the paw movement of the rat required to depress the lever. Thus the environment is linked to observable behavior by information processing. The pattern recognition of the triangle, the retrieval of its significance, and the programming of the appropriate action describe the observable behavior. The claim is that neither the physiological nor the intentional level will capture the knowledge gleaned from the information-processing level. As Churchland (1984) describes it, the aim is to provide ''the functional organization of the human nervous system'' (p. 92), and I would simply add ''interacting with the environment.''

## An Example of a Computational Model

We might make some headway into an answer to the need for a computational level of explanation if we consider more fully what to expect from a model theory of some phenomenon. A model should represent the phenomenon of interest in an informative manner. It should not be identical to the phenomenon; if it were, then it would no longer be a model but would be the phenomenon. We want a model or simulation, not the actual phenomenon or a duplication. Let's consider a model theory of speech production first proposed in 1848 by the German physiologist Johannes Müller (Dudley & Tarnoczy, 1950; Flanagan, 1972). Speech production is conceptualized in terms of a sound source's being activated and passed through a filter. Additional components can be added to simulate other features of speech production. Figure 20 illustrates a mechanical model of speech production that anticipated the formal source-filter theory. For the articulation of a vowel, the source is the vibration of the vocal folds, and the filter is the vocal tract.

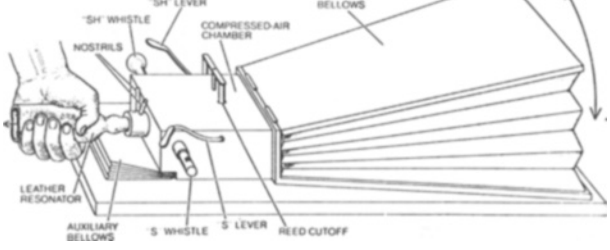


**Figure 20. Mechanical model of speech production anticipating the source-filter theory of speech production. From "The speaking machine of Wolfgang von Kempelen" by H. Dudley and T. H. Tarnoczy, 1950, *Journal of the Acoustical Society of America*, 22. Reprinted by permission of the publisher.**

The vibrating vocal folds can be simulated by a vibrating body producing a source spectrum. The vocal tract is simulated by a filter corresponding to a series of open tubes connected to one another and varying in diameter and length. This model theory has been used many times to create both hardware and software speech synthesizers (Cohen & Massaro, 1976; Klatt, 1980). In this sense, the model theory has proven successful and might be considered adequate and even necessary for understanding speech production. This theory might be considered to be computational, since it is neither physiological nor phenomenological.

The source-filter theory certainly is not simulating the microstructure of the speech production system, nor is it representing the phenomenal level of speech production. It seems to be capturing an intermediate computational level. Although no one has proposed this theory as a psychological model of speech production, the model might be fantasized as a mental model to illustrate what the computation level might contribute to understanding, over and beyond the physiological and phenomenological levels. In controlling speech production, we might consider motor programs that would specify parameters separately for the source and filter functions. To convey various affective states, the source parameters could be varied without modifying the filter parameters. Hence, the speaker might appear excited or depressed on the basis of his or her tone of voice, independently of the message content. Analogously, the parameters specifying vocal-tract shape might be modified slightly to convey a regional dialect, when appropriate, without modifying those parameters specifying the sound source. This computational level appears to add to our understanding and explanation over and beyond what could be given at either the micro or macro levels. Analogously, the claim is that the computer metaphor is valuable for understanding perception and action, an understanding not completely achieved at the other two levels.

## Two Levels of Description

The computational approach can be justified because information-processing theory is informative at a level of psychological description. The computer metaphor requires a psychological description, in addition to a purely physiological description. If a scientist comes upon a computer and wants to understand how it works, different levels of inquiry are possible and necessary. Following one line of inquiry, an electronics engineer could tear the computer apart and describe the physical makeup of the computer. This description provides information about the physical components, such as whether the memory in the computer is composed of a magnetic core or semiconductor chips. Even given a complete physical description of the hardware, however, a curious person still might not be satisfied with respect to how the computer works. Very little would be known about the software. The scientist would not know what programs the computer uses, how those programs work, whether the computer learns, forgets, or can do two things at the same time. The distinction between the hardware and software levels of a computer is emphasized by many computer languages that disguise the hardware of the machine. The same program can be run on a variety of computers that are fundamentally different in their hardware makeup. The significant issues addressed at the level of the programs of a computer are very similar to the questions asked about people. To study the software of the computer, we would want to observe the computer in operation. We would manipulate the environment in certain ways and see how the computer reacts to those manipulations. This is how psychological functioning is studied in humans. The environment is manipulated in an orderly manner, and we see what consequences it has for the subject. From the relationships between the changes in the environment and changes in behavior, we hope to learn something about the hidden psychological operations involved.

The distinction between physiological and psychological levels of description is analogous to a distinction made in artificial intelligence, a field of computer science aimed at creating intelligent machines. The designing of machines to resemble human intelligence might follow one of two principles. In the first instance, the hardware of the machine is made to imitate the brain as much as possible. The binary or on-off logic of a computer might be viewed as analogous to the all-or-none behavior of brain cells. An example of this approach is the neural-net approach of perceptrons (Minsky & Papert, 1968; Rosenblatt, 1958). In the second approach, intelligence is modeled by the manipulation of symbols, as on a digital computer. In this information-processing view, the computer's ability to process information is viewed as analogous to a human's ability to process information. In this case, the programs or software of the machine might be designed to mimic human thought processes (Newell & Simon, 1956, 1972; Simon, 1969). Until a few years ago, contemporary thought and research in artificial intelligence appeared to have adopted the information-processing over the brain-imitation approach (Raphael, 1976; Winston, 1977). One might even say that intriguing and challenging realizations of artificial intelligence have materialized within the information-processing model. More recently, there has been a revival of simulating brain processes as much as possible (Feldman, 1985; Hinton & Anderson, 1981), but the distinction between the two levels of description is still real and valid.

Marr (1982) maintained the two different levels we have taken for granted within the information-processing paradigm and added a third, top, level. At the top level is computational theory: the goal and logic of the computation specified at the information-processing level. J. J. Gibson (1966, 1979) made us aware of the top level in terms of the functions that the perceptual system accomplishes. This is why he had been a spokesman for artists and applied visual scientists long before being accepted by psychologists. However, Gibson would not acknowledge the need for an information-processing level, and did not provide a convincing rationale for how information could be picked up without information processing (Massaro, in press a). At the middle level within Marr's framework, we have structure and process. The structure specifies how the input and output are represented; the process specifies the nature of the operations for the transformation between input and output (Massaro, 1975a). At the bottom level is the physical realization of the information processing. As reiterated by Mehler, Morton, and Jusczyk (1984), the middle and bottom levels are only loosely related, and an adequate understanding at one of these levels does not ensure an understanding at the other level. Even if we were able to locate the neurophysiological mechanism, it is unlikely to constrain the algorithms and representations being used at the information-processing level.

### Mapping Between Levels

What is important about maintaining different levels of description is that a one-to-one mapping between levels is unlikely. Contrary to the increasing trend in the field, the neurophysiological level of description cannot be taken as a direct index of the psychological level (or the reverse). For this reason, the psychological level of description is informative even if the description at the neurophysiological level is complete. We do not understand some psychological process, such as pattern recognition, by simply localizing it in the brain. As an example, findings of common brain sites involved in perception and production of language, rather than supporting a motor theory of perception, might simply reflect a common mechanism used by both perception and production (Mehler et al., 1984). We have different objectives for the different levels of explanation, and a valuable model at the psychological level might not be directly reflected in a neurophysiological model. Mehler et al. (1984) make an important distinction between causation and descriptive explanations. Even if schizophrenia were caused by a biochemical defect, it would be still necessary to give a processing-model account of schizophrenic (and nonschizophrenic) behavior. I have provided a similar justification for a psychological theory of reading (Massaro, 1984a).

The importance of a psychological level of description was apparent when I recently confronted the latest work (Okita, Wijers, Mulder, & Mulder, 1985) in electrophysiological response potentials (ERPs). If these measures are tapping brain function directly, we might expect less need for a psychological model to make sense of the observations. But, in fact, ERPs seem fruitful primarily as a dependent variable that can illuminate psychological function. This variable can do so not simply because ERPs tap brain activity but because the brain activity is being examined in the light of experimental and theoretical analyses at the psychological level. In this sense, ERPs are compatriots of RT and accuracy with no privileged status as more direct indices of psychological function. Analogously, brain damage and brain activity actually might be more informative when analyzed at the psychological than at the physiological level.

My pet peeve about the science of localizing function is the study of hemispheric asymmetries. It is now clear that there is no one-to-one mapping between hemispheric advantage and the putative localization of function. In speech, for example, a number of dimensions produce a right-hemisphere advantage (Blumstein & Cooper, 1974), and, therefore, speech perception cannot be localized in just one hemisphere. In addition, hemispheric differences vary with attention, memory, and response strategies (Freides, 1977; Kinsbourne, 1978). I also wonder how many dichotic listening studies have not seen the light of day because the results came out in the "wrong" direction. As pointed out by Mehler et al. (1984), localizing the function can distract us from seeking to understand the nature of the processing. Analogous to a view of attention (Massaro, 1975a), a theory of hemispheric differences can only follow, not precede, a theory of psychological functioning.

Thus, it is meaningful to understand the software or programming level regardless of the biological or electronic structure it is instantiated on. As noted by MacKay (1984), the current computational approach resembles the cybernetic approach. Their function is to give an intermediate conceptual level that affords a working link between the level of conscious agency and the level of neural activity. The existence of different levels of explanation is fundamental to the question of the computer metaphor in psychological inquiry. Following Bieri (1984), the question of interest might be formulated in terms of having three explanatory strategies for psychology, as illustrated in Figure 21. These three strategies correspond to three different levels of reductionism, spanning the continuum from the molecular to the global. Although we describe three different levels, the boundaries between them might be considered to be fuzzily rather than categorically defined. At the bottom level, the properties of physics and neurophysiology are used to explain behavior. At the middle level, an information-processing system, conceptualized in terms of a program and its functions, is used to explain observable behavior. At the top level, a person is conceptualized as an intentional system in which beliefs and desires (intentional states) are used to rationalize behavior. Within this framework, the mind-body problem reduces to the relation among the levels, and the issue of the computer metaphor reduces to the usefulness of the middle level.

One might, especially if one is an ecologically oriented scientist, conceptualize a fourth level (Owens, 1985). Here, behavior would be explained as part of a larger interactive system, that is, the organism functioning in its ecological niche. Although the more global level of description has proved useful (Gibson, 1979) and promises to shed light on the other levels, it does not solve the mind-body problem as formulated here, nor does it disambiguate the question of a computational level of explanation.

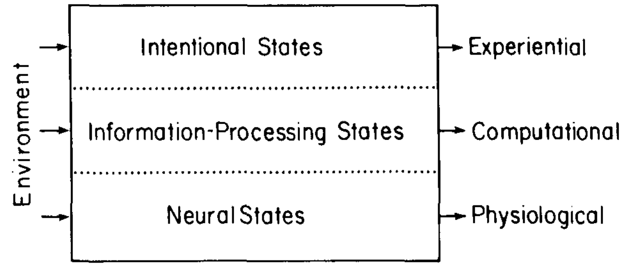


**Figure 21. Three levels of explanation in psychological inquiry (after Bieri, 1985).**

The existence of different levels of explanation is fundamental to the question of the computer metaphor in psychological inquiry. This issue leads to the first of six criticisms of the computer metaphor that I would like to consider. These criticisms give us the opportunity to explore the value of the metaphor itself, as well as giving us the opportunity to improve the metaphor to make it even more valuable.

## SIX CRITICISMS OF THE COMPUTATIONAL METAPHOR

### Searle's Criticism

The traditions of materialism in philosophy and behaviorism in psychology reject any role for a middle psychological level of explanation. In recent argumentation, John Searle (1984) has delineated some of the strongest arguments against the necessity of an information-processing level of explanation. In his view, psychology might be viewed as a century-old enterprise of failures to fill the gap between the neurophysiological and intentional levels. Introspection, behaviorism, cybernetics, and artificial intelligence have not succeeded. According to Searle, two levels of explanation are sufficient, and the interaction between the bottom and top levels is not symmetrical. The lower level can have an immediate cause at the higher level, but not the reverse. Any influence of the higher level on the lower level must be delayed in time and mediated by the lower level. For Searle, the asymmetry is justified by our belief in reductionism and because it supposedly precludes metaphysical problems with the notion of causality when higher order properties are assumed to cause lower order properties.

What is important for our purposes is Searle's hypothesis that we don't need the computational level between neurophysiological and phenomenological levels. His well-known disproof of artificial intelligence as a model of behavior involves a person's successfully communicating in Chinese without understanding. The person succeeds by following a rulebook for matching the incoming symbols, representing the input message, with symbols to be provided as the outgoing message. The idea is that the translator would have a syntax without a semantics. Thus a computer without a semantics cannot be said to understand English even if it succeeds in passing a Turing test. What is necessary to understand is what the symbols (words) mean. I am not convinced by Searle's critical *gedanken* experiment, however, because the information-processing level of the computer metaphor allows for semantic content as well as syntax. In fact, the psychological reality of heuristics, relative to algorithms, as information-processing explanations in many behavioral contexts, attests to this fact. The former might be thought of as having a greater contribution of semantics (knowledge states) than syntax (operations of these states). The information-processing view holds that pattern recognition results in semantic content, not just syntax (Allport, 1984). An important explanatory level for understanding language is neither at the intentional nor the physiological level, but at the information-processing level. We simply need a functional analysis of mind (Pylyshyn, 1984).

### Computation and Limited Capacity

If any criticism can be leveled at the computer metaphor, it might be in terms of limited capacity. George Miller (1956), Colin Cherry (1953), and Donald Broadbent (1958, 1971) acknowledged the primary contribution of communication theory for the concept of capacity. Miller viewed the magical number $7 \pm 2$ as a reflection of limited capacity. Cherry and Broadbent (Figure 22) studied the limitations in our ability to process information arriving simultaneously to multiple channels. Today, many are questioning the usefulness of such a concept (Cheng, 1985; Heuer, 1985; Kantowitz, 1984; Navon, 1984; Neumann, in press). A concern for demonstrating capacity limitations or nonlimitations seems to have distracted many of us from discovering how the processes themselves really work. Rather than being content to show that individuals can or cannot optimally perform some task, the goal should be to delineate the laws describing the processes involved in the task. What is important is not so much whether attention is necessary to conjoin two properties in pattern recognition, but the nature of the processes involved (Massaro, 1985).

Miller (1956) and Broadbent (1958) operationalized the concept of a limited-capacity channel in terms of the metric of information theory. Humans were supposedly limited in their rate of information transmission or reception when measured in bits per unit time. As an example, reaction times were shown to increase with increases in the number of alternatives in the task (Hyman, 1953). What is significant for our purposes is that the concept of limited capacity was internally consistent with the root metaphor of information. In contrast, Kahneman (1973) and others (e.g., Norman & Bobrow, 1975) extended the limited-capacity concept beyond the domain of information to the domain of effort. Here we seem to return to the metaphor of energy, and when combined with the concept of information, which Kahneman maintained, we have a mixing of metaphors. A decade later, enthusiasm for capacity and resources seems to be deflating quickly. The reason is that the limited-capacity question is unproductive, certainly as long as we allow multiple resources as an explanation or permit physical and structural kinds of interference to be interpreted as limited capacity. The consensus might be that the question has been a distraction from more important ones. Thus, a bad marriage between computation and limited capacity should not be taken pejoratively, since the concept of computation is neutral with respect to it.

**Figure 22. Donald E. Broadbent. Photograph printed with permission of Donald E. Broadbent.**

It was also the case that early computers were limited in many ways, such as having only a single central processing unit. As pointed out by Schweikert and Boggs (1984), however, this is no longer the case. We now have more powerful machines and the computational metaphor no longer necessitates serial processing and limited capacity.

### Computation and Indirect Realism

Carello, Turvey, Kugler, and Shaw (1984) attempted to explain the attraction to the computational metaphor on the basis of our erroneous pretheoretical notions of what requires explanation. They saw indirect realism as the root of the problem. Since the time of Herman von Helmholtz (Figure 23) and Franciscus Donders (Figure 24), much of empirical psychology has operated on the assumption that the sense data we have available are related equivocally to the environment as it must be understood. Internalized cognitive processes are necessary to operate on the sense data to provide such understanding. Since these processes can be represented in terms of simple algorithms rather than homunculi, they are attractive to the scientific community. Gibson (1979), of course, offers the alternate perspective of direct realism. If the important aspects of the environment can be detected directly with no computation, such a notion can be exorcised at least from explanatory models of perception. However, much of perception involves decision making and memory, processes compatible with the computer metaphor. Whether perception is direct or indirect is orthogonal to the value of the computer metaphor. For our purposes, I just want to reject the neo-Gibsonian equation of the computational metaphor with indirect realism.

### The Human Component

Dreyfus (1979) and others have been skeptical of simulating blood and guts by machine or computation. How can we capture or explain animal action, such as the emotion observed by Darwin (see Figure 25), at the symbolic level? What these criticisms miss, however, is the nature of explanation and modeling. A model, theory, or simulation is a representation of the real thing; it is not the real thing. If it were, it would no longer be a model, theory, or explanation. I fail to see a qualitative difference between cognitive and emotional behavior, and there is no reason to reject the computational metaphor for the emotional side of cognition.

### Uncovering Computational Processes

An important criticism is that it is not possible to eliminate explanations at the computational level. The particular theoretical framework that is chosen is arbitrary. The more we learn about some phenomenon, it seems the number of possible explanations only increases, or at least remains relatively fixed. Consider what might appear to be a straightforward question within the context of horse-race models of psychological function. If two horses are in a race, relative to just one, what are the possible consequences? Early experiments showed that detection reaction times (RTs) to the combination of a light and a tone were faster than RTs to either the light or the tone presented alone. The attractive explanation at the time had to do with intersensory facilitation: stimulation of one modality enhances the stimulation produced by a stimulus to the other modality. However, Raab (1962) observed that the results can be explained by assuming variability in the finishing times of the horses in the race. With this assumption, there is no evidence for a cross-modal interaction or cross-talk. The finishing time of the first horse in a two-horse race will, on the average, be faster than the finishing times of the two horses racing separately. He described the outcome as "statistical facilitation." Thus, if we assume that the detection time for the light has some variability and the same is true for the tone, then average RT to the pair will be somewhat faster than to either signal presented alone, simply because of statistical facilitation.

With this revelation, investigators during the next two decades were informed and required a larger RT difference than that predicted by statistical facilitation to conclude that the horses were interacting in the race (Gielen, Schmidt, & van den Heuvel, 1983; Miller, 1982). Results indicated that the facilitation was greater than that predicted by statistical facilitation, and the idea of independent horses in the race was rejected. However, even though we should have known better, the statistical facilitation model assumed that the only variability in the RT had to do with the process of interest (e.g., detection time). We know only too well that the RT also includes response selection and motor execution times and that these surely contain variability. If the variability from these other processes is substantial, then a model assuming independence between the two horses makes predictions very similar to those of a model assuming interactions between the two horses. Thus, we have yet to provide a definitive answer to what seems to be a straightforward question about mental processes.

The horse-race example seems to support the criticism that it is difficult to eliminate alternative explanations and to uncover computational processes. However, progress can be, and is being, made. What is required, as in all scientific endeavor, is a fine-grained analysis (Oden, 1984). Kepler was troubled by the 8′ of arc deviation between the actual orbit of Mars and that predicted by Ptolemaic theory. Scientific inquiry at the computational level should exploit good scientific practice as it does in other domains of natural science. The information-processing paradigm is perfectly compatible with the frameworks of falsification (Popper, 1959) and strong inference (Platt, 1964). This strategy, along with a fine-grained analysis, is capable of providing major constraints on explanatory processes and mechanisms.

### Computation and the Discrete Mode

I believe that many of the apparent limitations of the symbolic representation and information-processing metaphor are due to its alignment with the discrete, rather than the continuous, or analog, mode. That is, information is usually conceptualized as being represented discretely, and processing is seen as the transformation from one discrete representation to another. Pattee (1974) also has criticized the current emphasis of cognitive science on the discrete mode on the grounds that it ignores the continuous dynamic mode. As an example of the overextension of the discrete mode, pattern recognition is described as the integration of a set of distinctive features that is present or absent to select unambiguously one of a fixed set of alternatives. Few scientists have seriously

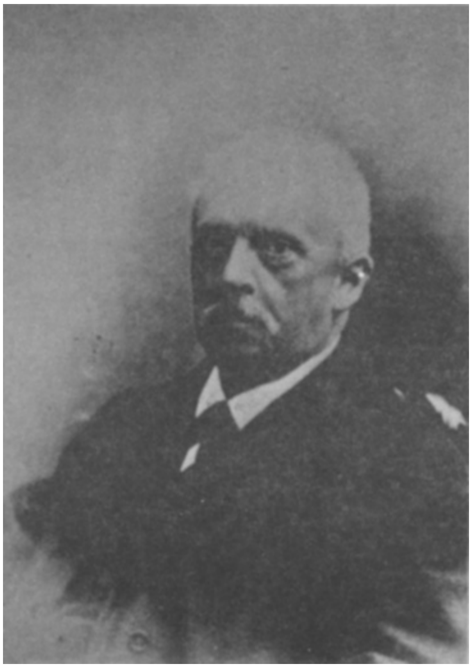

Figure 23. Hermann Ludwig Ferdinand von Helmholtz, 1821–1894.

Figure 25. Disappointed and sulky emotions, by Darwin.

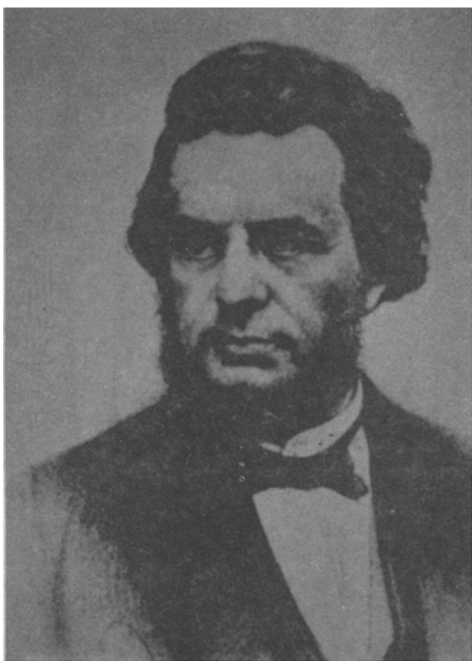

Figure 24. Franciscus C. Donders.

Figure 26. Clark Hull.

considered the alternative, and most go to lengths to conserve the discrete mode. Readers have no trouble recognizing letters in different type fonts, and such skill might be nicely described within the context of continuous information. However, rather than taking such a tack, the assumption has usually been that we have different discrete features for different type fonts. (e.g., Smith, 1971).

We have inherited a construct for the continuous mode, usually called strength, as in habit strength (Hull, 1943), response strength (Luce, 1959), or memory strength (Wickelgren & Norman, 1966). (Clark Hull is shown in Figure 26.) This concept went out of vogue with the decline of behaviorism and mathematical psychology and the onset of the information-processing framework. Rather than argue for a revival of this construct, I would like to consider a form of continuous representation that can be easily incorporated into the computational metaphor. In a similar fashion, Allport (1984) has observed that modality-specific representations are not inconsistent with the symbolic mode of information processing. The continuous mode does not compromise the power of the symbolic level of description (see also Kosslyn, 1983). Early in the history of computational models, Oliver Selfridge (1959) (Figure 27) assumed continuous rather than discrete degrees of shouting of the demons in his pandemonium model of pattern recognition. As many of you have anticipated, I am talking about the fuzzy logic and fuzzy sets invented by Lotfi Zadeh (Figure 28) (Goguen, 1969; Zadeh, 1965, 1984). In fuzzy logic, propositions are neither entirely true nor entirely false, but rather take on continuous truth values. For example, we might say that a meal is somewhat spicy. Ordinary logical quantification would require that the meal be either spicy or not. In contrast, fuzzy logic allows us to represent the nature of things as continuous.

It should be stressed that fuzzy truth is different from probability, primarily because probability maintains the discrete mode, whereas fuzzy logic does not. The appropriate contrast for probability is determinism, not discreteness. A probabilistic event means that the event either occurs or does not occur with some probability. It does not mean that the event occurs to some degree. If we say that a whale is a mammal to degree .8, it does not mean that there is a .8 probability that a particular whale is a mammal. Rather, it is true that the whale is a mammal to degree .8. The mammal category must be stretched somewhat to include whale, but whale is included to degree .8.

**Figure 27. Oliver Selfridge. Photograph printed with permission of Oliver Selfridge.**

**Figure 28. Lotfi Zadeh. Photograph printed with permission of Lofti Zadeh.**

It is unfortunate for psychological theory that Zadeh (1965) dubbed this view of continuous truth as "fuzzy," because continuous representation in no manner implies the common meaning of fuzziness. When we say a whale is a fish to degree .2, we are not necessarily any less confident of this proposition than we are of the proposition that a robin is a bird to degree 1. The difference between discrete versus continuous truth values might be a more descriptive contrast than that between standard logic and fuzzy logic. Since the principles of fuzzy set theory were direct generalizations of standard set theory, "fuzziness" misses the contrast between the two logics. In related work on concepts and categorization, Mervis and Rosch (1981) observed that the representation of the concept does not have to be fuzzy, even though a particular instance fits the concept only to some degree.

The empirical question is whether our symbolic representations are continuous or discrete. I would like to mention a few of our tests of this question within the domain of speech perception (Massaro, 1984a; in press a, in press b). Speech perception is the ideal domain in which to find evidence for the continuous mode, because it is so widely accepted that speech perception is categorical (as witnessed by our textbooks and popular journals such as *Scientific American*). Three pieces of evidence argue for the continuous over the discrete mode of representation in speech perception. The first involves testing formal models of continuous and categorical perception against the perceptual judgments of speech events involving the orthogonal variation of audible and visible speech. The second measures RTs of the perceptual judgments. The third test addresses the ability of subjects to rate reliably the degree to which a speech event resembles a perceptual category. All results support the continuous over the discrete mode. In addition, the results can be adequately described by a computational model in which the sources of information are represented continuously. Thus, we have good reason to expand our symbolic level of description from discrete to continuous.

## ALTERNATIVES TO THE COMPUTER METAPHOR

Churchland (1984, p. 92) proposed that there are three criteria to assess the success of the functional approach to mind. In formulating and testing computational hypotheses, the first criterion is that the hypothetical computational system must account for the input-output relations of the cognitive faculty under study. That is, it must simulate or model what the selected faculty does. However, as we all know too well, there are many different computational procedures that will produce some finite set of input-output relations. Churchland (1984) gave the example of a small calculator computing the value $2n$, given the value $n$. In addition to multiplying by 2, it might multiply by 6 and then divide by 3, and so on. (Actually, for the psychologist, a table lookup for the answer, versus some mathematical procedure, would be a contrast of more interest.) The second criterion is that the ingenious psychologist must pursue fine-grained analyses of various tasks to eliminate alternate explanations. These include the temporal course of the behavior and the nature of errors that are made. The third criterion is that the computational procedures must be consistent with the underlying physiology (however, this constraint is practically meaningless given the current state of knowledge in this domain; see Mehler et al., 1984).

### Methodological Materialism

Churchland (1984) apparently had no real criticism of this approach but offered methodological materialism as the better alternative: Since cognitive activities are simply activities of the nervous system, the best way to understand those activities is by understanding the nervous system. He was also optimistic about progress in this area of research. I have two complaints. First, the progress made at the level of the nervous system does not seem to overwhelm that made at the information-processing level. Second, understanding the nervous system independently of the organism's functioning in its environment will not explain what we are interested in explaining. A satisfactory account will include a psychological level of description (Pylyshyn, 1984).

### A Skills Approach

Kolers and his colleagues (Kolers & Roediger, 1984; Kolers & Smythe, 1984) have rejected the information-processing approach but not the symbolic level. "Mental life is intrinsically symbolic" (Kolers & Roediger, 1984, p. 445). As one alternative, they have proposed the study of mind as a skill in manipulating symbols, analogous to the study of motor skills. As evidence against the information-processing metaphor, they have cited the literature demonstrating the primacy of surface features over semantic features in the acquisition and retention of spoken and written language (e.g., Kolers & Ostry, 1974). By varying the orientation of the type of written sentences, Kolers and Ostry (1974) asked whether the learning and memory of the sentences would be influenced by this "superficial" feature. Subjects read normal or inverted sentences and some time later were asked to read the same sentences mixed in with some novel ones. Subjects indicated whether each sentence had been read before and, if it had, whether the visual appearance was the same as in the original reading. The inverted sentences were recognized more accurately than those presented in normal orientation, arguing for specific memory of the original orientation.

This result was explained by Kolers and his colleagues in terms of procedures or the acquiring of information from an object by means of pattern-analyzing operations. I doubt that results of this nature, although valuable, provide a serious challenge to information processing, or evidence for a skills approach (whatever it is). Recently, Horton (1985) demonstrated that the advantage of reading spatially transformed text emerges because of the elaborate semantic memory extracted during the initial presentation of the test sentence. When objects have both graphemic and semantic information present during the recognition phase of the experiment, they appear to rely exclusively on the semantic information. It seems improbable that the conceptualization of memory as a skill will be a robust enough metaphor to replace that given by information processing.

### New Connectionism

As mentioned earlier, there is an impressive growing research enterprise involving the production of behavior phenomena emerging from the simulation of brain processes (Feldman, 1985). To understand this new connectionists' movement, it is helpful to review the old connectionists' perceptron (Minsky & Papert, 1968; Rosenblatt, 1958). As far as I can tell, the perceptron has all of the essential ingredients of the current parallel distributed processing (PDP) theories within the new connectionism. Rosenblatt rejected the language of symbolic logic and Boolean algebra and formulated his model in terms of probability theory. His goal was to model the nervous system in a more realistic manner than was possible with the von Neumann metaphor using symbolic logic. However, it is important to note that Rosenblatt was proposing a theory at the hardware level rather than at the software level [a point also made recently by Broadbent (1985) with respect to the new connectionists]. In Rosenblatt's model, a signal is transduced by sensory units and impulses are transmitted to association cells via a projection area. The connections between the projection and association areas are random. The response cells receive impulses from a large number of association cells. Connections in both directions are established between the association and response cells by coactivation and feedback. This system can learn to associate specific responses to specific stimuli and to generalize to new stimuli of the appropriate class. Thus, it appears to solve the fundamental problems of pattern recognition without assuming any higher level operations, such as those of feature evaluation, integration, and decision making (Selfridge, 1959).

At first glance, a theory of this form would appear to offer a substitute for the information-processing level of symbolic representation and algorithm. The reductionists (Krech, 1955) would applaud such a move. In actual practice, however, the implementation level of the theory mixes the connectionistic level with the symbolic level. For example, McClelland and Rumelhart (1981) found it necessary to assume that subjects had different processing and decision criteria to predict performance differences under different experimental conditions. Thus, the psychological result of interest had to be explained outside of the domain of the connectionist theory itself. This example and others illustrate that description within the new connectionist framework will not necessarily eliminate the need for a psychological level of explanation. It is my opinion that the connectionist theory is not adequate to explain psychophysical and psychological performance because the level of description is neurophysiological and not psychological. The latter is necessary to make sense of the phenomena requiring explanation. More recently, Ackley, Hinton, and Sejnowski (1985) agreed that multiple levels of explanation are necessary; they believe that it is necessary to bridge the gap between the hardware-oriented connectionistic descriptions and the more abstract symbol manipulation models.

What we sometimes forget is that neural models are also metaphoric; that is, they are models, they are not the real thing. As noted by Gentner and Grudin (1985), however, they are less detectable as metaphors and less subject to the analytical scrutiny that leads to greater precision and systematization. They seem to convey greater face validity because of the value we place on reductionism in scientific inquiry (Krech, 1955). One might use this observation to justify the current honeymoon with the new connectionist movement.

In summary, we might ask two questions with regard to this movement. First, does it provide a real alternative to the von Neumann machine? Second, does it eliminate the value of computational models aimed at providing a psychological level of description? With respect to the first question, the von Neumann machine is controlled by means of a program stored in memory. The activation and inhibition links among hypothetical neurons or nodes in parallel distributed-processing models might be conceptualized as a stored program. In this sense, the two types of machine do not seem that different. The second question is answered readily if the connectionistic models are conceptualized as addressing a neurological rather than a psychological level of description, also noted by Broadbent (1985). One should not view these models as a challenge to delineating laws and constraints at a psychological level.

## AN EXAMPLE OF INQUIRY AT THE COMPUTATIONAL LEVEL

The computational level is useful because it increases our understanding of behavior. It is my belief that neither the phenomenological nor the neurophysiological levels of explanation could provide the same kind of understanding. A decade later, I believe that our (Massaro, 1975b) information-processing approach to language understanding was productive and anticipated many of the issues that are extant today. I would like to illustrate this belief further by discussing a smidgen of my research on bimodal speech perception, or how we perceive speech by ear and by eye, if for no other reason than to provide fuel for Alan Lesgold's (1984) claim that this Presidential Address is exploited usually for talking about one's research.

My research has been guided by the information-processing paradigm, along with the framework of falsification and strong inference (Platt, 1964; Popper, 1959). Binary oppositions are constructed and tested; for each opposition, multiple tests are implemented so that no conclusion rests on just one or two observations. Given the scope of this address, however, I will be able to present only an illustration of the research. The reader interested in the research enterprise is referred to other papers (Cohen, 1984; Massaro, 1984b, in press a, in press b; Massaro & Cohen, 1983). Although visual speech distinguishes among only a subset of speech contrasts (Walden, Prosek, Montgomery, Scherr, & Jones, 1977), visual speech appears to be utilized by the hearing perceiver in face-to-face communication. An auditory-visual blend illusion provides the most direct evidence of this fact (MacDonald & McGurk, 1978; McGurk & MacDonald, 1976). What we see clearly influences what we perceive in speech perception. For example, pairing the sound /ba/ with a seen /ga/ articulation is usually recognized as /da/.

If both auditory and visual sources of information are utilized in speech perception, it seems only natural that the two sources should be integrated. Integration of two sources of information refers to some process of combining or utilizing both sources to make a perceptual judgment. However, demonstrating that two sources are integrated in perceptual recognition is no easy matter (Massaro, in press a). A perceiver might utilize the auditory source on some trials and the visual source on other trials, giving the overall impression of integration even though it did not occur.

It might not be possible to demonstrate integration if subjects are tested only with a factorial combination of the two sources. By including judgments of the single modalities, however, the question of integration might be tested. Consider the perception of bimodal speech events created by the combination of synthetic speech sounds along an auditory /ba/ to /da/ continuum paired with /ba/ or /da/ visual articulations. By adding the single auditory and single visual cue conditions to the factorial design, as illustrated in Figure 29, it is at least logically possible to reject the possibility of a subject's using only one source on each trial. What is necessary is to find judgments of certain bimodal speech events that cannot be accounted for by judgments of the visual or auditory dimensions presented alone.

In our experiments (Massaro, in press a, in press b), subjects are usually asked to identify bimodal speech events, auditory-alone trials, and visual-alone trials. For the bimodal trials, an auditory synthetic syllable along a 9-step /ba/ to /da/ continuum is dubbed onto a videotape of the speaker saying /ba/ or /da/. In addition, the auditory speech stimuli are presented alone, with no lip movements, on some trials; and the /ba/ and /da/ articulations are presented without sound on other trials. The subjects are permitted an open-ended set of response alternatives.

For the question of integration, we limit our analysis to the occurrence of /bda/ judgments, shown in Figure 30. The pattern of occurrences provides strong evidence for a true integration of the auditory and visual sources. The critical finding is the large proportion of /bda/ judgments, given a visual /ba/ and an auditory /da/, when this same judgment is seldom given to either the visual or auditory modalities presented alone. We find over five times as many /bda/ judgments given to the bimodal events relative to the visual-only condition, and the auditory-only condition almost never produces /bda/ judgments. It follows that the /bda/ judgments observed on bimodal trials could not have resulted from identification of just one of the two sources on a trial. The result represents the outcome of the integration of both auditory and visual sources

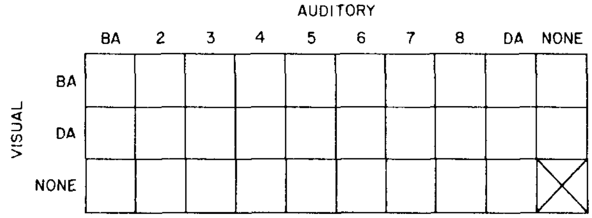


Figure 29. Expanded factorial design used in the study of speech perception by eye and ear.

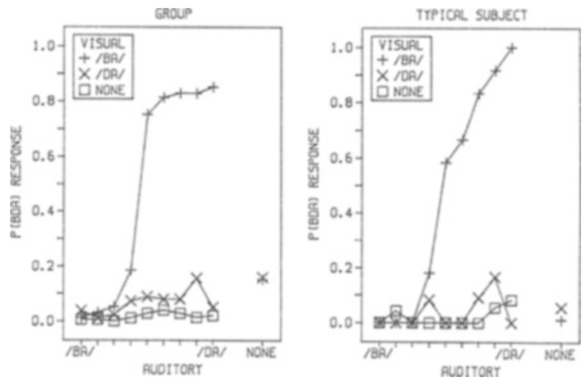


Figure 30. The proportion of /bda/ judgments as a function of the auditory and visual dimensions of the speech event.

of information, in that both contributed to a single perceptual judgment.

Integration seems to be an efficient system for perceiving speech. Given multiple sources of information that are susceptible to random variability, the optimal strategy would be to evaluate and integrate all of the sources, even though they might be ambiguous. One cost to a system designed in this way would be its relative inability to process selectively a single dimension of the speech event. Thus, subjects find it difficult to attend only to the auditory speech while looking at the speaker's lips, and vice versa (Massaro, in press a). These results demonstrate that integration is a natural process, and that we difficult to process selectively one dimension of the speech event without being influenced by other dimensions.

The nature of the integration process can be revealed by the types of judgments given conflicting sources of information. Consider the large number of /bda/ judgments given a visual /ba/ and auditory /da/, and the almost nonoccurrence of /dba/ judgments given a visual /da/ and auditory /ba/. In my opinion, these judgments depict a smart process with the following constraints. First, the auditory and visual sources are processed, to some level in the system, relatively independently of one another (i.e., without cross-talk). A second constraint is that some continuous representation is acquired about the auditory and the visual sources in terms of their compatibility with candidate categories.

Consider the large number of /bda/ judgments to a visual /ba/ combined with an auditory /da/ in terms of the visible and audible properties of a /bda/ category. The visible mouth movement for /bda/ is similar to the movement for /ba/. Thus, we can say that visual /ba/ supports both /ba/ and /bda/ alternatives. In addition, auditory /da/ supports the alternative /da/ and might even be considered to support /va/ and /tha/ to some degree. Thus, the system might be faced with auditory information that supports /da/ and visual information that supports /ba/ and

/bda/. Thus, /bda/ can be considered the appropriate identification because it maintains the most consistency between two dimensions of the speech input and the perceptual judgment.

The form of the explanation of /bda/ judgments takes on even more meaning because it can explain the rare occurrence of /dba/ judgments. Visual /da/ supports only /da/ (or /ga/) and to some extent /va/ and /tha/, but certainly not /dba/. The latter involves a closing of the vocal tract at the lips which is not contained in the /da/ articulation. The auditory information supports /ba/ and to some extent /va/ and /tha/ (as indexed by the auditory-alone condition). Thus, subjects report /tha/, /va/, and "other," given a visual /da/ and an auditory /ba/. The perceptual system seeks to reach the best compromise between conflicting visual and auditory sources; it will not decide completely in the direction of one source (no matter how unambiguous or invariant) if it flies in the face of another source.

Both the phenomenological and neurophysiological levels seem limited in their explanatory interpretation of these findings. The perceiver experiences a single speech event and finds it difficult to report on the separate modalities, even with extended practice. Thus, phenomenological reports cannot be taken as evidence for whether a single modality was used in the judgment or both modalities were used. How the cues were used would be well beyond any of our expectations of what phenomenological reports could provide. It is also difficult to imagine how neurophysiological recordings might shed light on the processes involved. We would expect to find activation of the appropriate visual and auditory pathways regardless of whether only one modality or both modalities were being utilized in the perceptual recognition of the speech event. It is unlikely that the neurophysiology will constrain sufficiently the various mathematical algorithms describing the integration of the two sources of information. Thus, the computational level appears to be informative and cannot be replaced by other, more molar or more molecular, levels of explanation.

## CONCLUSION

Our short journey confronted the value of the computer metaphor of the mind. It seems necessary to postulate a computational level of processing to explain and predict perception and action. Thus, cognitive scientists appear to be doing more than simply passing the time until the problem is solved by the neurophysiologists or even the environmentalists. Computation might be the level of explanation necessary to bridge the gap between environment and behavior. As I have discussed elsewhere (Massaro, 1984a, in press a), our safest strategy would be to utilize the tenets of falsification and strong inference in an empirical study of perception and action. The goal would be to obtain not necessarily laws à la Kepler, but important constraints on potential theories at any level of explanation.

## REFERENCES

Ackley, D. H., Hinton, G. E., & Sejnowski, T. J. (1985). A learning algorithm for Boltzmann machines. *Cognitive Science*, **9**, 147-169.

Allport, A. (1984). Alternatives to the computational view of mind: The baby or the bathwater? A commentary on Kolers and Smythe. *Journal of Verbal Learning & Verbal Behavior*, **23**, 315-324.

Bieri, P. (1985, January). What is the mind-body problem? Lecture presented at the Center for Interdisciplinary Research, University of Bielefeld, Federal Republic of Germany.

Blumstein, S. E., & Cooper, W. (1974). Hemispheric processing of intonation contours. *Cortex*, **10**, 146-158.

Broadbent, D. E. (1958). *Perception and communication*. New York: Pergamon Press.

Broadbent, D. E. (1971). *Decision and stress*. New York: Academic Press.

Broadbent, D. E. (1985). A question of levels: Comment on McClelland and Rumelhart. *Journal of Experimental Psychology: General*, **114**, 189-192.

Carello, C., Turvey, M. T., Kugler, P. N., & Shaw, R. E. (1984). Inadequacies of the computer metaphor. In M. S. Gazzaniga (Ed.), *Handbook of cognitive neuroscience* (pp. 229-248). New York: Plenum Press.

Chapuis, A. E., & Droz, E. (1958). *Automata: Historical and technological study*. Neuchatel, Switzerland: Editions du Griffo.

Cheng, P. W. (1985). Categorization and response competition: Two nonautonomic factors. *Psychological Review*, **92**, 585-586.

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. *Journal of the Acoustical Society of America*, **25**, 975-979.

Church, R. M. (1983). The influence of computers on psychological research: A case study. *Behavior Research Methods & Instrumentation*, **15**, 117-126.

Churchland, P. M. (1984). *Matter and consciousness: A contemporary introduction to the philosophy of mind*. Cambridge, MA: MIT Press.

Cohen, M. M. (1984). *Processing of visual and auditory information in speech perception*. Unpublished doctoral dissertation, University of California, Santa Cruz.

Cohen, M. M., & Massaro, D. W. (1976). Real-time speech synthesis. *Behavior Research Methods & Instrumentation*, **8**, 189-196.

Dretske, F. I. (1981). *Knowledge and the flow of information*. Cambridge, MA: MIT Press.

Dretske, F. I. (1985). *Explaining behavior* (Report No. 52). Bielefeld, Federal Republic of Germany: University of Bielefeld, Center for Interdisciplinary Research.

Dreyfus, H. L. (1979). *What computers can't do: The limits of artificial intelligence*. New York: Harper Colophon.

Dudley, H., & Tarnoczy, T. H. (1950). The speaking machine of Wolfgang von Kempelen. *Journal of the Acoustical Society of America*, **22**, 151-166.

Edwards, P. N. (1984). *Formalized warfare: Origins of cybernetic psychology*. Unpublished dissertation prospectus, University of California, Santa Cruz.

Evans, C. (1979). *The micro millennium*. New York: Viking.

Feldman, J. A. (1985). Connectionist models and their applications: Introduction. *Cognitive Science*, **9**, 1-2.

Flanagan, J. L. (1972). The synthesis of speech. *Scientific American*, **226**(2), 48-58.

Freides, D. (1977). Do dichotic listening procedures measure lateralization of information processing or retrieval strategy? *Perception & Psychophysics*, **21**, 259-263.

Gentner, D., & Grudin, J. (1985). The evolution of mental metaphors in psychology: A 90-year retrospective. *American Psychologist*, **40**, 181-192.

GIBSON, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton Mifflin.

GIBSON, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

GIELEN, S. C., SCHMIDT, R. A., & VAN DEN HEUVEL, P. J. M. (1983). On the nature of intersensory facilitation of reaction time. *Perception & Psychophysics*, **34**, 161-168.

GOGUEN, J. A. (1969). The logic of inexact concepts *Synthese*, **19**, 325-373.

HEUER, H. (1985). Some points of contact between models of central capacity and factor-analytic models. *Acta Psychologica*, **60**, 135-155.

HINTON, G. E., & ANDERSON, J. A. (1981). *Parallel models of associative memory*. Hillsdale, NJ: Erlbaum.

HORTON, K. D. (1985). The role of semantic information in reading spatially transformed text. *Cognitive Psychology*, **17**, 66-88.

HULL, C. L. (1943). *Principles of behavior*. New York: Appleton-Century-Crofts.

HYMAN, R. (1953). Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology*, **45**, 188-196.

KAHNEMAN, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

KANTOWITZ, B. H. (1985). Channels and stages in human information processing: A limited analysis of theory and methodology. *Journal of Mathematical Psychology*, **29**, 135-174.

KINSBOURNE, M. (1978). *Asymmetrical function of the brain*. Cambridge, England: Cambridge University Press.

KLATT, D. H. (1980). Software for a cascade/parallel format synthesizer. *Journal of the Acoustical Society of America*, **67**, 971-995.

KOLERS, P. A., & OSTRY, D. J. (1974). Time course of loss of information regarding pattern analyzing operations. *Journal of Verbal Learning & Verbal Behavior*, **13**, 599-612.

KOLERS, P. A., & ROEDIGER, H. L., III. (1984). Procedures of mind. *Journal of Verbal Learning & Verbal Behavior*, **23**, 425-449.

KOLERS, P. A., & SMYTHE, W. E. (1984). Symbol manipulation: Alternatives to the computational view of mind. *Journal of Verbal Learning & Verbal Behavior*, **23**, 289-314.

KOSSLYN, S. M. (1983). *Ghosts in the mind's machine: Creating and using images in the brain*. New York: Norton.

KRECH, D. (1955). Discussion: Theory and reductionism. *Psychological Review*, **62**, 229-231.

KUHN, T. S. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

LESGOLD, A. M. (1984). Human skill in a computerized society: Complex skills and their acquisition. *Behavior Research Methods & Instrumentation*, **16**, 79-87.

LOFTUS, G. (1985). Johannes Kepler's computer simulation of the universe: Some remarks about theory in psychology. *Behavior Research Methods, Instruments, & Computers*, **17**, 149-156.

LUCE, R. D. (1959). *Individual choice behavior*. New York: Wiley.

MACDONALD, J., & MCGURK, H. (1978). Visual influences on speech perception processes. *Perception & Psychophysics*, **24**, 253-257.

MACKAY, D. M. (1984). Mind talk and brain talk. In M. S. Gazzaniga (Ed.), *Handbook of cognitive neuroscience* (pp. 293-317). New York: Plenum Press.

MARR, D. (1982). *Vision: A computational investigation into the human representation and processing of visual information*. San Francisco: Freeman.

MASSARO, D. W. (1975a). *Experimental psychology and information processing*. Chicago: Rand-McNally.

MASSARO, D. W. (Ed.). (1975b). *Understanding language: An information processing analysis of speech perception, reading and psycholinguistics*. New York: Academic Press.

MASSARO, D. W. (1984a). Building and testing models of reading processes. In P. D. Pearson (Ed.), *Handbook of reading research* (pp. 111-146). New York: Longman.

MASSARO, D. W. (1984b). Children's perception of visual and auditory speech. *Child Development*, **55**, 1777-1788.

MASSARO, D. W. (1985). Attention and perception: An information-integration perspective. *Acta Psychologica*, **60**, 211-243.

MASSARO, D. W. (in press a). Information-processing theory and strong inference: A paradigm for psychological inquiry. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action*. Hillsdale, NJ: Erlbaum.

MASSARO, D. W. (in press b). Speech perception by ear and eye. In B. Dodd & R. Campbell (Eds.), *Hearing by eye: Experimental studies in the psychology of lip reading*. Hillsdale, NJ: Erlbaum.

MASSARO, D. W., & COHEN, M. M. (1983). Evaluation and integration of visual and auditory information in speech perception. *Journal of Experimental Psychology: Human Perception & Performance*, **9**, 753-771.

MCCLELLAND, J. L., & RUMELHART, D. E. (1981). An interactive activation model of context effects in letter perception: Part I. An account of basic findings. *Psychological Review*, **88**, 375-407.

MCCORDUCK, P. (1979). *Machines who think*. New York: Freeman.

MCGURK, H., & MACDONALD, J. (1976). Hearing lips and seeing voices. *Nature*, **264**, 746-748.

MEHLER, J., MORTON, J., JUSCZYK, P. W. (1984). On reducing language to biology. *Cognitive Neuropsychology*, **1**, 83-116.

MERVIS, C. B., & ROSCH, E. (1981). Categorization of natural objects. *Annual Review of Psychology*, **32**, 89-115.

MILLER, G. A. (1951). *Language and communication*. New York: McGraw-Hill.

MILLER, G. A. (1953). What is information measurement? *American Psychologist*, **8**, 3-11.

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, G. A. (1981). *Language and speech*. San Francisco: Freeman.

MILLER, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology*, **14**, 247-279.

MINSKY, M., & PAPERT, S. (1968). *Perceptrons*. Cambridge, MA: MIT Press.

NAVON, D. (1984). Resources—A theoretical soup stone? *Psychological Review*, **91**, 216-234.

NEISSER, U. (1967). *Cognitive Psychology*. New York: Appleton-Century-Crofts.

NEUMANN, O. (in press). Beyond capacity: A functional view of attention. In H. Heuer & A. F. Sanders (Eds.), *Perspectives on perception and action*. Hillsdale, NJ: Erlbaum.

NEWELL, A., & SIMON, H. A. (1956). The logic theory machine. *IRE Transactions on Information Theory*, **IT-2(3)**, 61-79.

NEWELL, A., & SIMON, H. A. (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice-Hall.

NORMAN, D. A., & BOBROW, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology*, **7**, 44-64.

ODEN, G. C. (1984). Dependence, independence, and emergence of word features. *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 394-405.

OKITA, T., WIJERS, A. A., MULDER, G., & MULDER, L. J. M. (1985). Memory search and visual spatial attention: An event-related brain potential analysis. *Acta Psychologica*, **60**, 263-292.

OWENS, D. A. (1985). [Comment on P. Bieri's (1985) lecture]. Unpublished comment.

PATTEE, H. H. (1974). Discrete and continuous processes in computers and brains. In M. Conrad, W. Guttinger, & M. D. Cin (Eds.), *Physics and mathematics of the nervous system* (pp. 128-148). New York: Springer-Verlag.

PLATT, J. R. (1964). Strong inference. *Science*, **146**, 347-353.

POHL, I., & SHAW, A. (1981). *The nature of computation: An introduction to computer science*. Rockville, MD: Computer Science Press.

POPPER, K. (1959). *The logic of scientific discovery*. New York: Basic Books.

PYLYSHYN, Z. N. (1984). *Computation and cognition: Toward a foundation for cognitive science*. Cambridge, MA: MIT Press.

RAAB, D. H. (1962). Statistical facilitation of simple reaction times. *Transactions of the New York Academy of Sciences*, **24**, 574-490.

RAPHAEL, B. (1976). *The thinking computer: Mind inside matter*. San Francisco: Freeman.

ROSENBLATT, F. (1958). The perceptron: A probabilistic model for information storage and organization in the brain. *Psychological Review*, **65**, 386-407.

SCHWEICKERT, R., & BOGGS, G. J. (1984). Models of central capacity and concurrency. *Journal of Mathematical Psychology*, **28**, 223-281.

SEARLE, J. (1984). *Minds, brains and science*. Cambridge, MA: Harvard University Press.

SELFRIDGE, O. G. (1959). Pandemonium: A paradigm for learning. In *Mechanization of thought processes*. London: Her Majesty's Stationery Office.

SHANNON, C. E. (1948). The mathematical theory of communication. *Bell System Technical Journal*, **27**, 379-423, 623-658.

SIMON, H. A. (1969). *Sciences of the artificial*. Cambridge, MA: MIT Press.

SMITH, F. (1971). *Understanding reading*. New York: Holt, Rinehart & Winston.

TOULMIN, S. (1972). *Human understanding: Vol. I. The collective use and evolution of concepts*. Princeton, NJ: Princeton University Press.

TRASK, M. (1971). *The story of cybernetics*. London: Institute of Contemporary Arts, Studio Vista Ltd.

WALDEN, B. E., PROSEK, R. A., MONTGOMERY, A. A., SCHERR, C. K., & JONES, C. J. (1977). Effects of training on the visual recognition of consonants. *Journal of Speech & Hearing Research*, **20**, 130-145.

WICKELGREN, W. A., & NORMAN, D. A. (1966). Strength models and serial position in short-term recognition memory. *Journal of Mathematical Psychology*, **3**, 316-347.

WIENER, N. (1948). *Cybernetics*. Cambridge: MIT Press.

WILLIAMS, J. M. (1978a). Antique mechanical computers: Part 1. Early automata. *Byte*, July, 48-58.

WILLIAMS, J. M. (1978b). Antique mechanical Computers: Part 2. 18th and 19th century mechanical marvels. *Byte*, August, 96-107.

WINSTON, P. H. (1977). *Artificial intelligence*. Reading, MA: Addison-Wesley.

ZADEH, L. A. (1965). Fuzzy sets. *Information & Control*, **8**, 338-353.

ZADEH, L. A. (1984). Making computers think like people. *IEEE Spectrum*, **21**, 26-32.