Certainty recent developments in experimental psychology

BY NEAL E. MILLER

Psychology Department, Yale University

(Lecture delivered 21 March 1963—Received 29 April 1963)

I am sure that every speaker must tell you, as indeed he certainly feels, that it is a great honour to have the opportunity to present a paper to your Society, which has such a distinguished role both in the history and in the most recent advances of science. I am glad to have this opportunity to speak to you.

Upon being asked to talk on this topic, however, I became acutely aware of how active a field experimental psychology is today. Each year Psychological Abstracts publishes summaries of approximately 9500 articles presumed to be relevant to some branch of psychology. Of these approximately 1300 are in human experimental psychology and 1400 in comparative and physiological psychology, or a total of something like 2700 in the general area of experimental psychology. I cannot hope to do justice to such an avalanche of material. The best I can do is to give you a few brief samples from certain actively developing areas, but other equally active areas might just as well have been chosen. In order to be impartial, I have excluded my own work on motivational effects of electrical and chemical stimulation of the brain and on conflict behaviour,* which I have had ample opportunity to present in lectures elsewhere in your country.

Recently, experimental psychologists have shown increasingly great interest in studying how organisms process and act upon information. The mathematical development of information theory and cybernetics has contributed greatly to this work (Shannon & Weaver 1949; Wiener 1948). But there are other tributaries to the torrent. A remarkable little book on Thinking published by your own Sir Frederic Bartlett in 1958 has had significant impact, the full force of which is just beginning to be felt. He shows the continuity between such apparently different activities as skilled perceptual-motor performance on the one hand, and thinking and the use of language on the other. Work on the processing of information illustrates an important fact about modern experimental psychology, namely, that it stretches all the way from physiology to sociology, and that the boundaries with other disciplines, such as acoustics, engineering, medicine, and linguistics, are being crossed with increasing frequency. Across this vast territory, I shall try to spot in a few samples beginning with a physiological study of the sense organs and mentioning studies of attention, memory, language, problem solving, and the effects of infant experience.

To begin at the sense organs, a familiar object seen on various occasions at different distances, or from different angles, or under different conditions of illumination, is the source of an enormous number of quite different patterns of retinal

stimulation, and yet is quickly responded to with a remarkably constant recognition. We usually take this for granted, but if one stops to think about and experimentally study the human capacity for various perceptual constancies, it is truly miraculous. Now we are beginning to understand how this remarkable feat of information processing is accomplished.

Work by many investigators, some physiologists and some psychologists, shows that each stimulated sensory element in the retina exerts an inhibitory effect upon impulses from its neighbours. This process automatically sharpens the discontinuities that exist at the border between a lighter and darker area of illumination. The dark units at the edge are most inhibited by the activity of the bordering brighter ones, making a dark line at the edge, and the brighter ones fire more rapidly since they are subject to inhibition from only one side, making a bright line next to the dark one. This mechanism emphasizes the contours of objects, and it is known that contours play an important role in object recognition under a great variety of conditions. For example, a line drawing, or a cartoon, contains much less visual information than a photograph, but it usually contains a high proportion of the relevant information. Thus some processing, which emphasizes relevant information, occurs in the retina (Ratliff 1961).

More recently, Hubel & Wiesel (1963) have used microelectrodes to record from single cells in different parts of the visual system in the brain of the cat. In the lateral geniculate body, which is a smaller, phylogenetically more primitive part of the central visual system through which the impulses are relayed first, they found specific cells that would fire when a specific part of the retina was stimulated by a tiny circular patch of light. Such cells were inhibited by illumination of the surrounding area, so that each of them responded best to a localized spot of difference in brightness, rather than to an absolute level of brightness. With other cells the situation was exactly the opposite, so that they responded to localized spots of relative darkness.

In the striate cortex, which is a much larger and phylogenetically more recent structure, they found many cells that responded in an entirely different manner. For these cells overall changes in illumination were ineffective and the responses to single spots were minimal. Certain cells responded to a line of brightness running in a specific direction on a specific part of the retina. A given one of these cells apparently received connexions from each of the cells responding to the spots of brightness on a specific line.

Cells responding to lines running in the same direction were gathered together in columns, among which would be found cells responding to any line of brightness running in that direction irrespective of its specific location on the retina. A given one of these cells presumably receives connexions from each of the cells responding to each of the different parallel lines. The complexity of the connexions required is reduced greatly by the grouping of such cells together in columns.

It can be seen that the foregoing mechanism abstracts a generalized concept—line of brightness running in a given direction—from the illumination of specific retinal points. In doing this it reduces an enormous amount of specific information, on level of illumination and on each of the exact points stimulated, to a much
smaller amount of highly relevant generalized information. We shall meet the process of information reduction in the discussion of other work, such as that on higher forms of concept formation and on thinking.

Hubel & Wiesel found similar organizations of cells for responding to other patterns, such as lines of darkness, horizontal edges with brightness above and darkness below, and horizontal edges with the darkness above. Some cells specialized in moving lines or edges or in movement in a given direction.

A consideration of the number of cells and connexions required for such abstractions shows why the visual cortex must be much larger than the lower centre, which in turn is larger than the optic nerve. Thus modern techniques are beginning to indicate a few of the simpler details of how information is processed from the concrete to the abstract in different parts of the nervous system.

FIGURE 1. A tentative information-flow diagram for the organism.

The foregoing results fit in nicely with earlier work showing that lesions in the visual system at higher levels in the brain interfere primarily with more abstract functions such as pattern recognition, while lesions at lower levels eliminate also simpler functions such as discriminating day from night. Different steps of information processing occur in different parts of the system. Some of this work has been done by experimental psychologists and some by physiologists; the departmental affiliation seems to be an arbitrary matter.

The next samples of recent developments in experimental psychology are organized around a flow diagram, presented in figure 1, taken from a provocative book on Perception and communication in which Broadbent (1958) summarizes a great deal of experimental work on human subjects, much of it by his own N.R.C. Group at Cambridge. This tentative information-flow diagram for the organism will be a convenient point of reference in sampling this work. We cannot do the many ingenious experiments justice and can only hope for mercy from their authors.

The 'limited capacity channel' in the centre of the diagram lends precision to the common-sense but inaccurate observation that one cannot do two things at
once. Indeed, one can do two or more things concurrently by using the short-term
store and shifting attention, represented by the filter, rapidly back and forth. But one
can do this only if the tasks do not demand processing information at too high a rate.

In one simple but convincing experiment a subject listens to a message delivered
by a phone to one ear. In a control test for physical masking, a buzzer is presented
unpredictably to the other ear. It produces no interference measured by objective
tests of correct responses to information from the message. But if the subject must
press a key every time the buzzer sounds, there is some interference. When the
alternatives are only buzzer versus no buzzer, only one unit of information, called
a ‘bit’, is being transmitted. But when the same buzzer is one out of a larger
number of possible alternative signals and responses, it carries more bits of
information, and the same episode of pressing a key to the buzzer produces more
interference. In all cases the interference occurs at the moment when the buzzer
sounds, or in other words, when additional information arrives. Many other
experiments with different techniques show similar results, namely, that the
interference produced by the same cue goes up with the number of alternatives
from which it is chosen, exactly as is predicted if the crucial variable is the amount
of information.

Now let us consider the feedback loop from the short-term store forward through
the selective filter and the limited capacity channel, and then back again to the
short-term store. You all know that after a single presentation, you easily can store
a reasonable sequence of digits, for example, a phone number, for a moment, and
retain it adequately by repeating it back to yourself from moment to moment,
provided you are not distracted by some other task which is too difficult. The
limit seems to be set by the amount of information in the number and the amount
of information in the distracting task, but it is not quite that simple.

Try to remember the number 149218627231416. This is difficult. But if you
notice that 1492 is the date for Columbus, 186272 is the speed of light and 31416
is π, the message recoded into three unitary symbols, or ‘chunks’—Columbus,
light, π—is very easy to remember, and you can reconstruct the more complicated
message from the simpler one. When one controls for recoding, the amount of
information that can be handled by short-term memory turns out to be seven
encoding ‘chunks’ plus or minus two, in a large number of different experiments on
a surprising variety of human tasks (G. A. Miller 1956).

The common sense view is that after one becomes practised at a task, it produces
less interference. Thus, for the novice driving interferes with carrying on a con­
versation, whereas for the skilled driver it does not—unless the traffic or conver­
sation is too difficult. But Bahrick, Noble & Fitts (1954) have shown that such
reduction in interference with practice is possible only when the task involves
predictable sequences (analogous to 31416) so that the performer can learn to take
advantage of these redundancies, and hence reduce the load of information
involved. Even then, there is a certain amount of interference with any other task
that involves a sufficient load of information. When the task being practised
involves completely random sequences, no amount of practice will reduce the
interference.
Now let us consider the type of experimental work that leads to the concept of a filter in the tentative flow diagram. If different messages are delivered simultaneously to the same ear, they will interfere with each other. But if the speakers of these messages have different voices, it is possible to reduce the interference by listening to one and ignoring the other. The fact that the subject can learn to pay attention to a specific type of cue is represented in the diagram by the arrow from the store of past events to the selective filter.

A considerable variety of experiments all agree in demonstrating that both the interference and the filtering are phenomena of the central nervous system, rather than involving peripheral masking or adjustments in the muscles of the ear. For example, with appropriate precautions, similar results are secured when both messages are delivered to the same ear by a single phone or when each message is delivered to a different ear. The detailed characteristics of this filter, and of messages that are most easily distinguished, are being determined by a large number of experiments (Broadbent 1958). The next time you arrive at a crowded airport, the application of such research to the control tower may well influence the safety of your landing.

Let us direct our attention next to the short-term store. Recently, various workers have realized that the traditional test of measuring the memory span by reading a series of digits to the subject and asking him to repeat them is a poor way of investigating such memory. There are two difficulties: the first digit must be stored longer than the last one before the subject begins to report, and the last one must be stored while the subject is making his report. As these deficiencies were realized, various ingenious techniques were devised to circumvent them.

I shall mention only one, selected because it is easy to describe and because it has forced an addition to the concepts represented on the diagram. It is well known that, when one uses the old method of requiring subjects to repeat the letters shown to them in a brief exposure, they can repeat only four or five. Auerback & Correll (1961) wondered whether this was a limitation based on the total capacity for initial storage, or whether the storage time was too short to allow read-out into a more permanent memory. In order to test for this, they exposed an array of 16 letters to subjects for 50 ms. At the end of this exposure they flashed a bar marker on to the screen to indicate which single letter, randomly chosen, was to be reported. Since the subject had no way of knowing what letters were going to be in the array or which position was going to be chosen, he had to store the whole array in order to be able to answer correctly.

When the bar marker coincided with the exposure of the array, the subjects were able to report correctly approximately 75% of the time. The fact that they could not report 100% presumably indicates difficulties with reading letters perfectly under these conditions of brief exposure.

When the bar marker came almost immediately after the end of the exposure of the array, there was practically no decrement in correct responses. Therefore, there must have been practically perfect storage for this brief time. As the interval between the end of the array and the beginning of the marker was increased, there was a marked decrement in performance, until after approximately 300 ms only
about 30% correct responses were possible. This amounts to an average of 4.8 letters out of the 16 and corresponds closely with the total of four or five letters which an unaided subject can report. Still further delays did not produce appreciably greater decrements, presumably because the subject had read out the letters from this exceedingly short store into a somewhat more permanent one.

It is also interesting to note that this temporary store, or image, could be erased. In experiments on erasure, if the letters and marker were exposed simultaneously and a circle around the position of the marked letter was exposed within 100 ms afterwards, the performance of the subjects was greatly reduced. That the image and its erasure are central effects in the brain, rather than being purely peripheral processes at the retina, is indicated by the fact that the letters could be presented to one eye and erased by a circle exposed in the corresponding position to the other eye. Other experiments of somewhat different types have demonstrated similar ‘erasures’.

The extremely brief duration of the store we have been discussing, the way it can be erased, and yet other characteristics, suggest that it probably is purely sensory, though central. Thus it probably is different from the true short-term memory store indicated in Broadbent’s diagram, and should be inserted in front of such a store. Various ingenious experiments are being performed to determine further how its properties differ from a true memory and what the properties are of the channel, or read-out process, between it and the short-term memory store.

One of the issues being investigated is whether man always acts as a stimulus sampling, intermittent system, or whether he really can deal with continuous stimuli by some kind of continuous process. This issue has given new significance and direction to an old type of research, namely, determining how specific conditions affect human reaction time (Welford 1960).

Stone (1960) has proposed the application of a general sampling theory to the prediction of reaction time. There are two basic notions: first, that the signal is mixed with a considerable amount of noise, and secondly, that the longer, and hence larger a sample one takes before reacting, the greater the probability is of basing the action on a reliable difference between signal and noise.

Mathematical formulation of this theory leads to the prediction that, as redundancy is increased, the reaction times of a thoroughly practised subject should become faster to the frequent cue and slower to the infrequent ones. It also predicts that the reaction time should vary with the values of each kind of success, the cost of each kind of error, and the costs and values of fast versus slow responses. Another prediction is that, once errors get down below 5%, large increases in reaction time should be required to make small decreases in the percentage of errors. Experiments confirming some of these predictions are described by Fitts, Peterson, & Wolpe (1963).

With the realization that the short-term store plays an important role in many types of performance ranging from perceptual-motor tracking to problem solving, and with the development of various new techniques for studying it, a new area of active research is developing. Melton’s (1963) recent paper on this topic cites twenty-four experimental studies published in the last 5 years. One of the issues
being investigated is whether the short-term memories established in a single trial obey the same laws as the longer-term memories, requiring more practice, which have been the subject of so much traditional research on human verbal learning since the early days of Ebbinghaus. Are these two different processes, as represented on Broadbent’s diagram (with the short-term on the upper left and the long-term on the lower right), or can they be shown to be the two ends of a functionally continuous process?

Many provocative similarities have been found between the way the short-term and the long-term memories are affected by a variety of experimental manipulations. But Brenda Milner’s (1959, 1962) studies of patients with a certain kind of lesion in the medial temporal lobes of the brain pose problems for the hypothesis of a functional continuum. The syndrome will be recognized as somewhat similar to one that sometimes occurs with old age. Such patients seem to have normal memory for events that occurred sufficiently long before the lesion, which also does not seem to interfere appreciably with complex tasks, such as carrying on a conversation, that involve only relatively short-term memory. Within the normal limits of information loading, these subjects can remember what they have just been told for as long as 15 min, provided they keep rehearsing it. The minute their attention is distracted, however, no trace seems to be left in memory. Thus when told of the accidental death of a dear friend, one such subject was greatly disturbed and talked continuously about the tragedy for some while. But after once having dropped the topic, the subject talked about this friend as though he were still alive, and whenever told of the accident, he showed no signs of having heard of it before. He went through this cycle repeatedly without learning.

Similar results have been secured in experimental studies of such patients. There seems to be a sharp dichotomy between the effect of the lesion on the ability to acquire new short- and new long-term memories; it is as if the lesion prevented the transfer of information from one to the other. However, one such subject did show improvement from one day’s session of mirror drawing to the next. Additional analysis with exact experimental techniques is needed to determine the precise nature and limits of this intriguing deficiency.

One of the regular findings of the older experimental studies of the long-term memory was that it is much easier to memorize meaningful than nonsense material. But in meaningful English prose, certain sequences of words are much more probable than others. To the extent that the occurrence of a word is determined by these sequential dependencies, the language is redundant, so that the amount of information per word is reduced. Less total information needs to be learned. Conversely, memorizing a nonsense (completely random) sequence of words requires the acquisition of more information as defined by information theory.

Miller & Selfridge (1950) required different groups of subjects to learn sequences produced by random selections from the 30 000 commonest words. Other sequences were created by an ingenious procedure which produced different approximations to the sequential dependencies of the English language without yielding meaningful material. In the first order of approximation, only the immediately preceding word was used to determine the subsequent ones. In the third order of
approximation, the three preceding ones were used, and so on. They found that the ease of learning increased up through the fifth order of approximation, which was approximately as easy to learn as passages taken from a novel. This was a presumably meaningful novel.

These results show that the amount of information to be acquired is a major variable in accounting for the greater difficulty of memorizing meaningless sequences of words. It remains to be seen, however, whether this conclusion about the role of information in the difficulty of learning can be generalized to tasks involving distinctive but highly unfamiliar non-verbal cues, for example, learning to arrange a number of strange odours into a specific sequence.

There is obviously much more to language than simple sequential dependencies which can be described by autocorrelational techniques. Its structure, or syntax, is governed by certain rules of grammar which have been intensively analyzed cross-culturally by modern linguists. Experimental psychologists are beginning to study these aspects of linguistic behaviour. For example, certain types of sentence structure, called right recursive or left recursive, are much easier to understand than another type, called embedded, which places a much greater demand on the short-term memory. Experiments are being designed to test various hypotheses about functional units of spelling-to-sound transformations and about the way subjects proceed in constructing sentences or in transforming one type of sentence into another (Gibson, Pick, Osser & Hammond 1962; G. A. Miller 1962).

Still another active area of interest in contemporary experimental psychology is that of human thinking and problem solving. An early view of problem solving was that subjects merely substituted more economical symbolic trial and error for more arduous and dangerous physical trial and error. Although a considerable amount of symbolic trial and error may be involved, this view has been shown to be unsatisfactory. Problems may be conceptualized as mazes or trees of alternatives in which solutions are sparsely scattered. Such trees are often very large, for example, the tree for the game of chess has some $10^{120}$ branches. Unselective searches of such large trees are utterly impractical. The problem solver must limit the range of trial and error by searching in a highly selective way.

There are many different ways to study problem solving. One of these is to train subjects to think aloud, so that they try to give a verbal report of each step they are following in the problem-solving process. Studies of the protocols secured in this way show that problem solvers do indeed search in a highly selective way which may be described, in part at least, in terms of certain rules of thumb called heuristic principles. One of these is means–end analysis. People analyze the problem situation into goals and subgoals and set out to find means of reaching the goal by solving one subproblem after another on the basis of their memory of steps which have been found useful in past problem situations. For example, a chess player may set up the subgoal of protecting a piece from capture. Considering various means of doing this might lead to a new subproblem, such as finding a safe square to move to (Newell, Shaw & Simon 1958).

Many psychologists have been sceptical of the thinking-aloud method. They have wondered whether it distorts the problem-solving process and whether the subject
can report all of the essential steps. Because of the complexity of the behaviour, it has been difficult to prove that heuristic principles, such as means–end analysis, actually are sufficient for solving a problem. To some psychologists these heuristic principles seemed trivial.

An increasing number of enthusiastic workers are attacking such questions with the help of computer-simulation techniques. These investigators do not use the computer as a calculator to solve mathematical equations; instead they use it as a general information-processing and symbol-manipulating machine. They are not interested in analogies between the wiring diagrams in the dry hardware of the computer and the wet software of the brain; their interest is in the program of the computer. They do not use the great speed of the computer to canvass an enormous number of alternatives, but instead program it according to hypotheses derived from observing human behaviour.

Trying to reduce means–end analysis, and other hypotheses about human problem-solving methods, to computer programs is a way of forcing them to be stated in explicit detail. It is not surprising that this turns out to be a difficult but useful discipline which ruthlessly exposes unsuspected weaknesses in a plausible literary exposition. When such a program is written, it becomes a rigorously stated theory of problem solving.

The first test of such a program (i.e. theory) is to see whether or not it will work in the computer to produce a solution to the problem. Such tests have been performed and after showing up a series of weaknesses which gradually were corrected, have proved that the postulated processes, such as means–end analysis and other heuristic principles, actually are sufficient for enabling computers to solve certain restricted, but significant, problems. Thus, Newell et al. (1958), who have been leaders in this field, have evolved a program which succeeded in proving 38 of the 52 theorems in chapter 2 of Whitehead & Russell's (1925) *Principia mathematica*.

Since then they have evolved a more general program which uses the same fundamental heuristics, not only to prove theorems from Whitehead & Russell, but also to solve the missionaries and cannibals puzzle which will be described presently, to prove trigonometric identities, and to write computer programs. This general problem-solving capacity, while still far short of that of the skilled human problem solver, is impressive.

The computer program is a possible theory of problem solving, but how adequate is it as a theory of human problem solving? That is a more difficult question.

One test for functional similarity is to see whether problems that are difficult for people are also the ones that are difficult for the computer. For example, it is easier for human subjects to prove the theorems in Whitehead & Russell if they are presented in the order that the authors present them. If an intermediate theorem is skipped, the problem becomes harder, and if enough intermediate theorems are skipped, it becomes impossible. This is also true for the computer.

Another test is to compare the steps taken by the computer, the relative time spent on different parts of the problem, and the places at which it failed, with the
protocols of human subjects. It should be pointed out that one does not directly take the steps followed by a human subject, program them into the computer and then have the computer spew these out again; if this were the goal, it would be much simpler to tape-record a protocol and play it back. One tries to abstract certain general principles of problem solution from the study of human protocols, then reduce these to a program to see whether or not it will solve a variety of problems. Thus one does not expect an exact correspondence with a human subject any more than one would expect two human subjects to take exactly the same steps in exactly the same time. Nevertheless, it is possible and useful to get some general idea of how the sentence-by-sentence output of the computer compares with the statements of human subjects solving the same problem.

With this much of an introduction, let me give a concrete illustration from a relatively simple problem—missionaries and cannibals. Three missionaries represented by three Ms, and three cannibals represented by three Cs, and a boat, B, are on the left-hand side of the river. The boat will hold only two men but can be rowed by one. The problem is to get all of them across the river under the condition that the number of cannibals in any one place must never exceed the number of missionaries, or else the cannibals would kill and eat a missionary.

The basic problem then is to remove a discrepancy between an initial state of affairs, every one on the left side, and a goal of every one on the right side. The human subject, or the computer, search for operations that will reduce this discrepancy. One of these is using a boat to take two people across. If the first manipulation is to remove two missionaries and a boat from the left to the right side, this produces a forbidden consequence and hence cannot be used. Taking two cannibals across is all right. Then one is faced with a new subproblem. One cannot take anybody else over because the boat is on the wrong side. The human subject and the computer search for ways of solving this subproblem. One way is to have two people row back. This would reproduce the same state of affairs one had before, a difficulty called 'cycling'.

Let us shift for the moment from the missionary and cannibals problem itself to the problem of designing a computer program to solve this problem. One can put in a specific test to eliminate any operation that produces cycling, but this demands that every previous move be remembered, which can build up to a severe demand on short-term memory established in a single trial. Actually, human short-term memory is quite adequate to eliminate cycles that are as short as the one just described, but human subjects often get trapped into longer cycles unless they use various techniques, such as writing down each move and searching back over all previous moves to see whether or not they are in a cycle, a procedure which can become quite cumbersome. Thus we see the relevance of research on short-term memory to the performance of problem solving.

Another solution to the computer programmer's problem is to introduce a progress test, selecting moves that contribute to increasing the number of people on the right side and discarding those that subtract too much in the pursuit of some momentary subgoal, such as getting the boat back. This is a strategy which human subjects seem to follow.
In this particular problem, however, there comes a time when it is necessary to send two people back in the boat. A number of highly intelligent human subjects fail to ever consider this move, or only come to it after having spent an inordinate amount of time on the problem, often cycling many times. Indeed, the difficulty of this problem, as in many puzzles, as opposed to the average problem met in life, is not so much that an enormous tree of alternatives must be explored as it is that one of the necessary moves runs counter to a mode of procedure that is generally useful in other situations.

Newell et al. (1958) found that one of the earlier versions of the General Problem Solver program had extreme difficulties with the missionary and cannibals problem for exactly the same reason that some bright people do, failure to even consider the move of sending two back in the boat at the point when that is necessary. It also was a weak problem solver because it tended to perseverate too long and fixedly on a given subgoal, generating the subsidiary sub-sub problem of trying to remove the difficulty in the way of solving that sub-sub goal, etc. Subgoals were never generated or considered except in the local context of the immediately superordinate goal.

Comparing the output of this version with human problem-solving protocols taught these investigators that this procedure was wrong. A provision was introduced to have the program review, from time to time, all new symbol combinations that had been generated to determine whether they contributed to progress on other subgoals than the one immediately responsible for their generation. This introduced a kind of serendipity into the search and greatly increased the power of the program.

While the missionaries and cannibals problem illustrates a very simple form of means-end analysis and the undesirability of too strict a progress test, the tree of possibilities is so simple that it does not illustrate the power of other heuristic principles. A readily understandable illustration of the value of heuristic principles comes from the problem of trouble-shooting complex electronic equipment, such as the radars used in the armed services. This will also serve as a simple example of a recent increase of interest in problem solving by a considerable number of investigators who prefer methods other than computer simulation.

When the task of trouble shooting was analyzed, it became apparent that two strategies, or a proper combination of them, would be useful. One strategy is to test first for the malfunctions that are statistically most frequent in a particular model of equipment. Another and more general approach is to use the type of strategy which most of us employ in the game of ‘Twenty questions’. Try to devise tests which will divide the possibilities into approximately equal halves, and then to go on subdividing the successively faulty subdivisions until you zero in on the source of the trouble.

These heuristic principles were not tested by devising a computer program; they were tested by use in an experimental training program which seemed to show that teaching these principles, along with some others involving systematic analysis of the symptoms, did improve the student’s ability to solve such problems. The analysis also suggested the desirability of minor changes in the design of the
equipment to facilitate the most efficient program of testing for the location of malfunctions.

The use of heuristic principles is further illustrated in a program which Simon & Simon (1962) have devised for discovering deep mating combinations in chess, or in other words, for planning ahead an attack near the end of the game from which it is impossible for the victim to escape. Tests with this program show that it can discover brilliant mating combinations without requiring amounts of search, memory, or processing speeds which are out of line with what is known about average human information-processing capacities. They conclude that various lines of evidence suggest strongly that expert chess players discover combinations because their ‘programs’ incorporate powerful selective heuristics, and not because they think faster or memorize better than other people.

The computer-simulation technique is being applied also to many other problems of behavioural science (Newell & Simon 1963). These range all the way from testing neurophysiological hypotheses—the Rochester et al. (1956) test of Hebb’s (1949) theory proved it to be inadequate—to testing complex hypotheses evolved to account for empirical data on how items of information spread through the social networks of a city or a rural area (Hagerstrand 1961). Examples of additional uses of mathematics and computers are given in Bush, Galanter & Luce (1963).

We have been considering studies of problem solving involving the computer-simulation approach. But this approach is only one of those involved in a renewed interest in studies of the higher mental processes. Some of these studies may be grouped around the notion of information reduction. You have already seen how presumably innate neural connexions in the retina, and in higher levels of the brain, serve to emphasize highly relevant aspects of sensory information at the expense of less relevant aspects. This selective process may be described as information reduction, since irrelevant information is discarded. A process of information reduction, which is similar in function although based on learning rather than innate connexions, plays an important role in thinking, forming concepts or extracting rules. It is what we mean when we say ‘getting to the heart of the matter’.

One of the functions of a good scientific concept, such as ‘mass’, is to allow the person faced with a particular problem to ignore large amounts of information, such as colour, shape and size, which are irrelevant to the solution of that particular problem. One of the functions of a good scientific law is to reduce a large array of data, which would be impossible to remember, to a simple formula that is easy to remember. In trying to accomplish such highly intelligent tasks of information reduction, we sometimes fall back on aid from the more primitive perceptual mechanism described at the beginning of this paper by plotting the points on log, or log-log, paper to see whether or not they fall on a line with a particular slope.

The foregoing way of conceptualizing certain types of intellectual activity is showing promise. Investigators are finding that it is possible to specify quite accurately the difficulty of certain intellectual tasks, within a given family of structurally similar tasks, by using quantitative measures of the amount of information reduction involved in these tasks (Posner 1962). For example, experiments on
concept formation (Walker & Bourne 1961) have shown that the number of errors made before arriving at the correct concept increases linearly with the amount of irrelevant information involved in the task, and that the slope of this line increases rapidly as one moves from tasks in which the definition of the concept requires only one bit of information, as in circles versus squares, to one that requires more bits, for example, large green circle.

One of the reasons why information reduction is so important is because human short-term memory is so limited. Thus a subject, who is exploring a certain hypothesis, rapidly reaches what Bartlett (1958) has described as a 'point of no return' beyond which he reacts only to information relevant to that hypothesis. If, however, human memory is aided by recording each step of the process, certain previously difficult problems of concept formation become easy (Cahill & Hovland 1960).

We have spoken of the use of computer simulation as a means of rigorously testing the logical outcome of complex theories. Some experimental psychologists are using the computer's capabilities in quite a different way. They are using it to present to human subjects complex, yet experimentally controlled, tasks, and also to score the performance on such tasks. In this way, learning that is of the degree of complexity encountered in the classroom is beginning to be studied with more rigorous control (Coulson 1962).

Other experimental psychologists are using the computer to present small groups of people with complex tasks, such as a simulated stream of information about the flight patterns of many identified friendly, and some conceivably hostile, planes (Carter 1962). The computer also scores the way the group handles this information in the process of making decisions. Such studies have demonstrated the remarkable capacity of skilled individuals and teams to deal with emergency conditions of overload by re-assigning priorities and neglecting or postponing the processing of information that is judged to be less urgent. In other words, the amount of information reduction is flexibly adjusted to the demand of the moment.

Other, much simpler types of programming equipment than the computer, have opened up new areas in the study of learning. In the older work, a specific reward was associated with a specific response in a simple all-or-none way. If the subject made a correct response, he received a fixed reward; if not, he got nothing. More recently, experimental psychologists have been studying the effects of subtler relationships between response and reward that approach more nearly the conditions of human social life. For example, a response may not always lead to a reward, but only increase the probability of a reward. It is interesting to find that, under such conditions, the response persists much longer, after reward is withdrawn, than it does if it has been rewarded on every trial. Similarly, specific correlations have been studied between dimensions of reward, such as amount or delay, and dimensions of response, such as rate, amplitude or latency. Such studies are changing our fundamental ideas about learning (Ferster & Skinner 1957; Logan 1960).

Thus far, I have made a narrow test boring along one dimension of experimental psychology, following the interest of laboratory workers in the reception and processing of information. I started at the sense organs and emerged with thinking,
problem solving and topics bordering on social psychology. My recent detour has mentioned another active area, that of learning, without doing that area justice.

In concluding my comments on recent developments in experimental psychology, let me strike off for a few moments in an entirely new direction. Another recent significant development has been the increase in interaction between the clinic and laboratory. Natural-history observation in the clinic has located significant aspects of human behaviour which are then investigated more rigorously in the laboratory.

The recent development of psychopharmacology is an example of this kind of work. Experimental psychologists learned long ago that it is not wise to ignore events within the organism that intervene between a stimulus input and a response output. Some of the most important intervening events are biochemical in nature. Changes in these biochemical events may be reflected in changes of behaviour. One of the most important developments in the clinical treatment of behaviour disorders, popularly called mental illness, is the use of drugs to control aberrant behaviour patterns. But intelligent use of drugs for this purpose requires systematic knowledge of the nature of drug-behaviour interaction, a need which has given rise to the development of the new area of research called psychopharmacology.

Work in Britain by the psychologists Eysenck (1957), Summerfield & Steinberg (1957), and Weiskrantz (1957) has contributed significantly to the rapid growth of research sophistication and knowledge in this field. Attention is being given not only to effects of drugs upon behaviour, but also to the use of drugs to alter specific biochemical events, such as neurohumeral systems within the body, which in turn are related to changes in behaviour.

One could give an entire lecture on psychopharmacology. But I want to conclude with a brief mention of another topic illustrating the interaction between the laboratory and the clinic.

In recent years there has been an acceleration of work on the effects of infant experience. Clinical observations have suggested that events during certain periods of infancy may have lasting effects on the adult personality. Bowlby (1952) has summarized data from ‘experiments of nature’ in which children are sent to certain types of orphanages or are temporarily separated by illness or other emergencies from their mothers and mother surrogates. Such data indicate that there are certain ages at which the effects seem to be especially damaging.

Meanwhile, ethologists, such as Lorenz, Hinde, Thorpe and Tinbergen (Scott 1962), have been observing that there are critical periods during which certain animals are subject to imprinting. For example, if a Mallard duckling, hatched in an incubator, is exposed during the critical period to a moving object, such as a person or a box on a trolley, it will tend to follow that object, rather than a mother duck. Dogs seem to attach their pack instincts to a human family, and sheep to acquire their gregariousness in a somewhat similar manner. Harlow (1962) has shown that monkeys isolated during infancy continue to display many abnormalities in adult life. The males fail to mate, and if the females finally are bred successfully, they do not take care of their offspring.
My concluding sample illustrates the advantages of a careful experimental analysis of the effects of infantile experience. Rearing puppies in isolation from the period of 3 to 12 weeks is known to produce relatively long-lasting deficits in their social and manipulative responses. Using a series of carefully standardized tests, Fuller (1963) and his colleagues studied these effects. A natural conclusion from these results would be that there is a sensitive period for the learning of the type of behaviour in which the deprived dogs were deficient, and that the dog loses its capacity for the type of learning required after this period is over. However, Fuller found that, if puppies reared in isolation were given a tranquilizer, chlorpromazine, during their first test session, their behaviour was much more normal. After 3 days of testing, the drug was withdrawn with no regression of behaviour.

These observations show that the rich normal environment was not necessary for the gradual learning of the items of behaviour in question, which probably were developing primarily by maturation, or on the basis of this maturation were learned very quickly during the test sessions under drug. Thus, it was not the deprivation per se which inflicted the lasting damage, but the sudden emergence from the deprived to the complex ‘normal’ environment. This conclusion was further confirmed by experiments showing that using a graded series of steps to introduce the dogs gradually to the test situation produces much the same effect as the tranquilizer.

Apparently this sudden emergence into a novel situation, at a time when the animal’s perceptual capacities were fully developed, elicited traumatic fears. These strong fears were conditioned to the cues in the normal environment. Therefore they persisted and continued to interfere with the performance of behaviour of which the animal otherwise would have been perfectly capable. This interpretation is supported by the fact that the dogs without tranquilizers showed an abnormal amount of cowering, trembling and retreat on the first test session and thereafter. Such a trauma apparently was avoided by the temporary use of a tranquilizer at this crucial juncture. Dogs receiving the tranquilizer did not show the symptoms of abnormal fear.

It is interesting to speculate that the sudden emergence produced its traumatic effect by overloading the dog’s information-processing capacity with too many novel stimuli, each of which had a high priority on the filter of attention. Be that as it may, the experimental analysis completely changed the conception of what was happening. It is clear that the impairment was not produced by a deprivation during a critical period essential for learning, but instead was produced by suddenly confronting the dogs with the novel and complex test situation.

In conclusion, you have seen the strong tendency for behavioural research to leap over the traditional boundaries between disciplines. The scientific method continues its vigorous advance into entirely new areas. I have sampled some of these advances in experimental psychology; similar ones are occurring in the adjacent social sciences. Such advances are additionally illustrated in a little report issued in my country by the Behavioral Sciences Subpanel (1962) of President Kennedy’s Science Advisory Committee. They are symbolized by the recent decision of the National Research Council in the United States to expand...
its original Division of Anthropology and Psychology into a new Division of Behavioral Sciences, including representatives from sociology, economics and political science, in recognition of the fact that an increasing number of the members of these disciplines are using scientific methods to study significant aspects of human behaviour.

Work on this paper was supported by Grant MY 647 from the National Institute of Mental Health of the U.S. Public Health Service.

REFERENCES


Fuller, J. F. 1963 Personal communication.


Miller, G. A. 1956 The magical number seven, plus or minus two; some limits on our capacity for processing information. *Psychol. Rev.* 63, 81–97.


