30 · *Teaching machines for perceptual-motor skills*

B. R. GAINES
Psychological Laboratory, University of Cambridge

Teaching machines have been developed for training and testing those skills involved in perceptual-motor tasks such as driving, piloting and tracking. These machines monitor the operator's performance and vary the parameters of his task accordingly, so as to maintain its difficulty at an optimal level as his learning progresses. It has been demonstrated that this is a viable technique for training and testing such skills, and the behaviour of this type of teaching machine is shown together with some results in its application.

Research on automated teaching has concentrated on cognitive and perceptual skills leaving perceptual-motor skills largely neglected. Motor skills are not verbalized and hence the introspective analysis which is essential to the teaching of cognitive skills is not available, and training is largely by example or through partial tasks. However, the lack of verbalization affects the approach of the designer rather than the problems he faces, and it is shown that teaching machines for motor skills are essentially similar to those for cognitive skills.

It is suggested that these machines will be of use in testing spatial and motor abilities, industrial training and rehabilitation and the evaluation of motor disability, together with driver and pilot training.

Introduction

Research on automated trainers for cognitive skills has reached the happy state where general acceptance of their utility enables effort to be directed to the design of good machines and programmes rather than to the justification of the means of training itself. This transition has yet to take place in similar work on automated trainers for such skills as typing, driving and flying which have a high perceptual-motor component, and research on teaching machines for perceptual-motor skills has been largely directed to providing some evidence of their usefulness rather than to optimizing one machine for a particular application.

The only major experiment reported to date is that of Hudson (1964) who showed significant tendencies for training conditions which were maintained at a level mid-range in difficulty for the operator to be better than those either easier or more difficult; Ziegler, Birmingham & Chernikoff

(1962) have described a 'teaching-machine for the selection and training of operators of higher-order vehicles', which removes 'quickening' in a tracking task as the operator's mean error decreases; Pask (1961) has developed a machine for training operators of card-punches in which cueing, rate of presentation and the difficulty of items are varied as a function of the latency and correctness of the operator's responses; and Kelley (1962) and Senders (1961) have each reported pilot experiments on automated trainers.

Such work however has been negligible compared with that on machines for teaching cognitive skills, although the military, industrial and medical potential of training aids for motor skills is very great. The reasons for this deficiency lie partly in our lack of knowledge of the structure of perceptual-motor skills and of the optimum conditions for their training, partly in the lack of introspection about such skills which would guide us despite this lack of knowledge, and finally in the technological difficulties and expense of constructing automated trainers – there is unfortunately no equivalent of the programmed text when teaching flying!

In this paper automated trainers for all types of skill are first discussed within the framework of general systems theory, where the concepts of complementarity and equivalence of roles enable research on both automatic control and human psychology to be used in a comprehensive analysis of the training situation. Distinctions between perceptual-motor and cognitive skills are then examined for their relevance to training, and details of the learning and performance of some simple perceptual-motor skills are given to illustrate essential similarities between all skills. Finally some experiments are described on the construction and use of teaching machines for perceptual-motor skills.

Man–machine interaction

Recent developments in automatic control and general systems research (Mesarovic, 1964) have clarified many features of man–machine interaction in control, testing, training, and guidance situations. The synthesis of controllers with multi-level strategies, such as adaptive controllers (Mishkin & Braun, 1961) and learning machines (Andreae), has made it possible to regard men and machines as equivalent system-components, and to utilize research on one in understanding the other. For example, techniques of education and training previously confined to man are now of importance in the fabrication of controllers, and strategies of learning developed for machines may be used to model those of man and guide the synthesis of training aids.

One system principle of especial relevance to the training situation is that of complementarity. A unitary system is closed and neither emits nor receives information or energy. If, conceptually, we divide the system into two parts and assign a role to one, for example adaptive controller or self-organizing system (Ashby, 1962), then the remainder of the system must assume the complementary role. More succinctly the remainder of the system must form a suitable 'environment' for the part which we have split away. If the environmental remainder is unfit to play a complementary role then we may be able to modify the system so that it can do so. For example, if one part of the system is assigned the role of 'controller' and the other part forms an unsuitable environment in that it has variations which cause the control loop to become oscillatory, then a minor control loop may be added specifically to limit these variations. Similarly if one part of the system is assigned the role of 'learning' and the other part forms an unsuitable environment in that it shows insufficient variety of behaviour, then another subsystem may be added which disturbs the environment contrary to the goals which the first part of the system is learning to achieve.

The introduction of another subsystem in this way may be treated either as a modification of the complementary environment, or as the interaction of two subsystems with a single environment. The system concepts appropriate to the latter interpretation are those of competition, co-operation and neutrality. If the role assigned to one system is made less easy to play by the addition of the other then this latter is said to be competitive, if more easy then co-operative, and otherwise neutral. Thus, in the last example above, the added system is competitive with respect to the role of 'controller' but co-operative with respect to the role of 'learner'. This particular example shows that relationships within a system are only established relative to the assignment of roles within it. These relationships become very rich when both controller and environment are adaptive and hence can assume many roles, and richer still when multiple rather than binary or ternary systems are considered. Competitive and co-operative systems have been examined mainly in game theory (Von Neumann & Morgenstern, 1944; Dresher *et al.*, 1964), and more recently in the control literature (Ho, 1965; Bryzgalov *et al.*, 1964).

Finally, but perhaps most important, the development of machines to play the roles previously assigned solely to man means that it is no longer necessary to conceive of one system-component as a man, another as a machine. A particular system may be realized with either or both, and, for example, experiments on learning situations and their manipulation may be carried out both with human operators and with machines. This equivalence also means that in practical systems it is not necessarily the man who is the adaptive, decision-making partner, and the machine which is the information-gathering, effecting partner. The course of evolution in machines has made such a clear division of labour less easy to discern, and more equable and flexible modes of co-operation are becoming apparent. In the next section a particular example of man–machine interaction which is not obscured by the complex phenomena of adaption will be used to illustrate these concepts.

Man as servant to the machine

A simple example of complementarity, co-operation and man–machine equivalence is the two-level controller in which a master–servant relationship subsists. This is illustrated in Fig. 1, where the upper controller *M* is ultimately acting on the environment *E*, but between *M* and *E* is a second controller *S*. There are many possible reasons for *S* to form part of the environment of *M*, but the most important are that *M* may have no channels of direct communication with *E*, and that *S* may be necessary to create and maintain conditions in *E* which make it a suitable complement for *M*. If *S* is present for communication purposes only and exerts no regulatory feedback, then it may reduce to a pair of transducers with some local feedback for their manipulation as shown in Fig. 2.

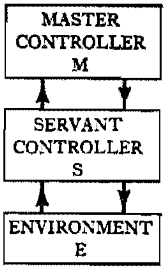

FIG. 1

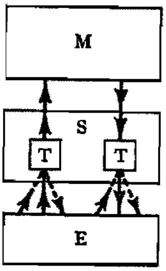

FIG. 2

Examples may be given of such two-level control within man and within machines which illustrate the complementarity induced by the master–servant relationship, but the interesting examples arise when one controller is a man and the other a machine, illustrating their equivalence with respect to roles. It is easy to think of a man as the upper controller or master, setting the temperature on a room thermostat or the parameters of an automatic pilot, but not so easy to think of man in the servant role. In fact examples of the latter are quite common, and their further development holds great promise for the use of teaching machines in 'guidance' situations. For example, servicing handbooks for electronic equipment prescribe a series of tests which may be carried out without comprehension by the serviceman (who is there because a machine to unsolder leads and connect meters is too expensive) until the necessary repair is established and carried out, equally blindly. Non-branching test sequences are mechanized in air force test-sets which have a roll of instructions built-in to be wound past a window as they are performed. The mechanization of branching structures, allowing continuous decision making by the machine, has been suggested more recently by Newman & Scantlebury (1964), who constructed a 'teaching machine' for the purpose of acting as the master controller and taking from the human operator responsibility for thinking out the test strategy and remembering the implications of past results.

The close co-operation of man and machine in a master–servant relationship exemplifies the changing pattern of use of man's skills. Whilst it is easy to automate logical procedures, data analysis and decision making in a digital computer, it is difficult to emulate man's capabilities of pattern recognition and perception (Lindgren, 1965), and his ability to carry out a motor-act leading to a prescribed goal, with very different effector patterns dependent on the initial configuration of his environment (Ernst, 1962). Man's perceptual-motor skills enable him to play a servant role as a versatile set of effectors and receptors with local regulatory feedback, and training for this role has assumed greater importance with mechanization of warfare and the automation of industry.

Varieties of learning

The equivalence of roles between man and machine is more recent in origin and less readily apparent when adaptive capabilities are considered. Men learn and machines may be used to teach them, but can machines learn and would we use men to teach them? An affirmative answer to both these questions is one of the most striking developments in modern automatic control. Man's adaptability is required in situations where man has not the time, the memory or the ability to adapt, and hence automatic devices have been developed to replace him. The complexity of such learning machines makes fabrication for specific purposes impossibly expensive, and hence the partial knowledge and ability of man are used to train a general-purpose machine. In the next sections the insight into the problems and techniques of learning gained through work on adaptive artifacts will be used to analyse training techniques.

Learning by example

Two main types of intelligent artifact may be distinguished: those which learn by example and those which learn by performing. Typical of the former are the Perceptron (Rosenblatt, 1964), Learning Matrix (Steinbuch, 1965) and Adaline (Widrow, 1964), which through 'watching' the behaviour of another system eventually become able to simulate it. Smith (1964) has applied the Adaline to the perceptual-motor task of balancing a rod by learning to simulate an automatic controller, and the human operator performing the same task has been used by Donaldson (1960, 1964) as an example for simulation by his Error-Decorrelator.

The training paradigm for machines which learn by example is shown in Fig. 3, where a training controller already capable of performing the task acts on the environment, and its inputs and outputs are taken to the learning machine which is to simulate it. The power of the learning machine depends on its ability to simulate the training controller in a wide range of situations, and this requires economical use of its storage capacity. Those above achieve this by a generalization procedure which makes their learning slow and accretive, and its rate highly dependent on the choice of training sequence (Nilsson, 1965). Fig. 4 illustrates the use of a trainer to vary the training sequence by manipulation of the environment or training controller in order to maximize the rate of learning. Feedback to the trainer from the state of the learning machine enables it to respond to the latter's particular needs, and may be obtained by direct observation, if possible, or by testing the learning machine's performance at intervals during training.

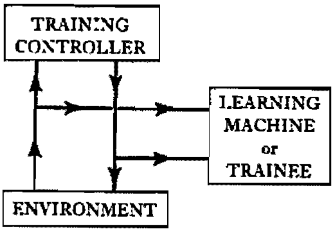

FIG. 3

This type of learning is simple in itself but may involve very complex processes of communication if the inputs and outputs of the exemplifying controller are not directly accessible to the learning machine. Learning chess by watching others is made very difficult through lack of information about what out of a welter of information is the player's immediate and decisive input and how many potential outputs he has tried and discarded – annotated games seek to overcome these difficulties but not all of chess strategy can be verbalized and annotated (Newell & Simon, 1965). Thus,

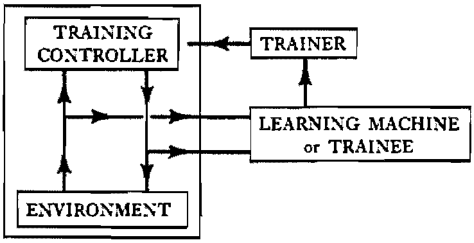

FIG. 4

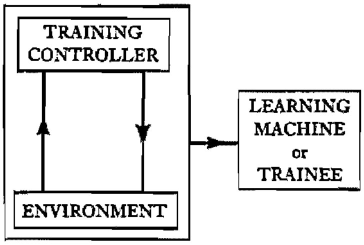

FIG. 5

when the paradigm of Fig. 3 is varied to that of Fig. 5, there is no guarantee that learning will still take place – watching a person riding a bicycle is no help at all!

To overcome these communication difficulties suitable channels must be established between the training controller and learning machine. For example, Holding (1965) has trained the human operator in a simple tracking task by using a servo as an example. Perceptual communication was established by using a discrete positional display in which no confusion could arise in the relative weights assigned to position, velocity, acceleration, etc., and motor communication was attempted by forcing the human limb movements to conform to those of the servo. Human language has developed to overcome such communication difficulties (Luria, 1961), and plays an important part in the learning of all skills, but language can be used only to communicate the macro-structure of a skill, the sub-goals which the micro-structure must be set to attain.

Learning through performance

Learning by performing differs from learning by example in that simulation of another controller is not possible, and the learning machine must proceed through trial and error, modifying its strategy according to its effects. If immediate feedback as to the correctness of actions is available then fairly simple machines may be built which modify their strategies towards optimality. If, however, feedback is given only as to the goodness of the overall strategy then the realization of an optimization procedure is very difficult.

Examples of machines using immediate feedback of performance are to be found among the adaptive model-reference controllers (Donalson, 1965; Stear, 1962) used in the control of high-performance aircraft. The human controller finds adaptation easy when the results of his actions are immediately apparent, and rapidly makes the adjustments necessary to compensate for changes of parameters in a simple tracking task (Young *et al.*, 1964). If feedback as to the goodness of a strategy is not conveyed action by action but comes when, after a sequence of behaviour the goal is attained, then learning is much more difficult. Andreae's STeLLA (1966) and Widrow's 'bootstrap learning' (1966) are examples of the mechanization of adaptation in these circumstances, and demonstrate the increase in memory requirements and logical complexity necessary under conditions of overall reinforcement. The human operator finds this situation equally difficult, and sports such as golf where feedback follows a long sequence of movements or tracking tasks such as piloting a ship or submarine, where the effects of actions are delayed, are very difficult and demand abilities not shared by everyone.

The implications for training are that if immediate feedback as to the correctness of actions can be made available then learning will be speedier (Bilodeau, 1961). Giving directly augmented feedback as shown in Fig. 6 is dangerous, however, as it may come to be relied upon for the purpose of performance and not used to aid learning (Briggs, 1962; Kinkade, 1963); a similar danger arises less subtly in learning by example when the trainee may be satisfied that the exemplifying controller is performing the task and not bother to learn it itself! At the other extreme is the possibility that no channel of communication for augmented feedback is available to the learning machine.

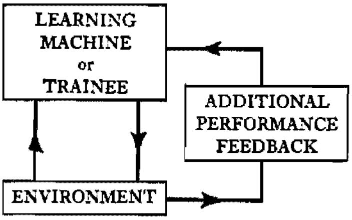

FIG. 6

These difficulties may be obviated by not giving a new form of performance feedback, but rather enabling the trainee to make better use of that which is already there. In tracking tasks the difficulty in obtaining immediate feedback as to the effect of actions is caused by superfluous activity in the display, generated through the instability of the control loop with a naïve operator, and a training controller which maintains the stability of the loop can make it possible for the trainee to see the effect of his actions; such a paradigm is shown in Fig. 7. Whilst most situations demand a co-operative training controller, the converse is required if the control task is simple and the trainee maintains too little activity in the display, whence a competitive training controller aids learning. The im-

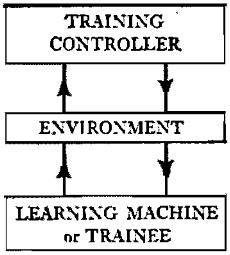

FIG. 7

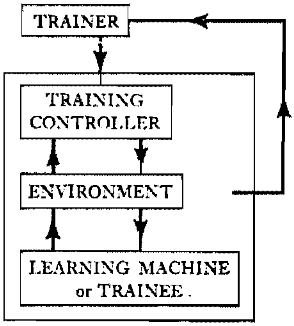

FIG. 8

portance of 'stability' in the teaching of any structured skill has been emphasized by Pask (1965), and the interaction of co-operating or competing controllers has been studied by Isaacs (1965) as a 'differential game'.

In the paradigm of Fig. 7 there is no means of eliminating the training controller and yet sooner or later this must be done, since the ultimate aim of training is to have the trainee perform the task himself (or, in terms of man–machine co-operation, some shift in responsibility is expected). The paradigm of Fig. 8 shows a trainer acting so as to vary the degree of co-operation/competition of the training controller, either eventually removing its effect entirely or maximizing its competition. In the next section the mode of operation of the trainers of Fig. 4 and 8 will be used to distinguish different types of training.

Varieties of training

The problem of the trainer is itself a control task (Gaines): the trainee has to be taken from an initial state where his performance is unsatisfactory to a final one where it is acceptable, and this has to be done quickly and efficiently. Four modes of training may be distinguished according to the trainer's strategy in performing this control task: in *fixed training* the trainee is given the required task immediately and reliance is placed on his ability to learn it outright; in *open-loop training* the trainer gives a fixed sequence of tasks which are suitably graded so that all trainees are bound to be able to follow or 'remain stable' – this is often necessary in teaching large classes where individual variation cannot be taken into account, and is of course the technique of linear or Skinnerian programmes; in *feedback training* the trainer decides on the next task according to the ability of the trainee – this obviously can be more efficient in fitting the needs of the individual, and is the technique of branching programmes; and finally in *adaptive training* the trainer's branching strategy is modified trainee by trainee so as to become best suited to the population of trainees. It is at this last stage that we may speak of the trainer itself learning, and such a process has been automated only through the use of a digital computer (Smallwood, 1962).

The feedback trainer utilizes information about the state of the trainee to manipulate the training controller, and it may be possible to establish a channel of direct communication between trainer and trainee to carry at least part of this information. The trainee has so far been considered to be a two-level adaptive controller, but the human operator is more complex and communication is possible both with the adaptive level and about it. In practice this means that the trainer may use verbal directives to describe a desired mode of control or encourage the establishment of one, and may also itself receive requests for the training conditions to be modified.

Pask & Lewis (1965) have used such a channel to prevent the trainee from attempting to establish one by the only means otherwise available – that of acting in a stupid or peculiar way upon the environment! The final paradigm for feedback training is shown in Fig. 9, where direct channels of communication between trainer and trainee supplement their previous 'communication' through environmental interaction. Any form of training may be carried out by this system ranging from a purely verbal or cognitive interaction between trainer and trainee as in conventional programmed learning, to purely perceptional-motor interaction as in a simulator. Neither extreme will be optimal for a given skill, and it is a combination of both in an *Integrated Training Environment* which proves most powerful.

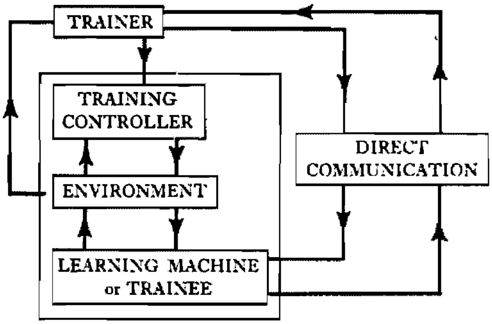

FIG. 9

Testing

Any feedback trainer may be used as a testing device since the training trajectory which it generates will vary according to the ability of the trainee. The use of a feedback trainer solely for testing purpose is especially attractive with perceptual-motor skills since fixed training and open-loop training are most common, and these are satisfactory only for sufficiently able trainees who must be selected by reliable tests; such tests may also be used to aid the human instructor (who is a 'trainer' requiring feedback). Conventional tests of skill measure performance on a fixed task and are insensitive since the operators tend to dichotomize into those who maintain loop stability and do well, and those who are unstable and do badly. Various techniques have been developed to make these tests more sensitive (Poulton, 1965), including that of 'secondary loading' (Knowles, 1963), where performance on an auxiliary task is used as a measure of the effort which may be diverted from the main task before it becomes unstable. However, the feedback training paradigm of Fig. 8 provides a very sensitive test of ability in terms of the co-operation required for the loop to be stable, and at the brink of instability no secondary loading is possible since all effort is diverted to the main task.

Distinctions between perceptual-motor and cognitive skills

So far no major distinction has been made between perceptual-motor and cognitive skills, especially those involving 'control' in its widest sense. Part of the purpose of this paper is to suggest that no distinction need, in theory, be made, and that it is only in practical or technical details that teaching machines for perceptual-motor and cognitive skills need differ. The main practical distinction is that in perceptual-motor skills the physical environment with which the trainee interacts is usually highly specific and virtually defines the skill, whereas in cognitive skills a 'pencil and paper' type of physical environment is common. This makes both for lack of generality and increased technological difficulty in the design and application of automated trainers for perceptual-motor skills.

Other distinctions between skills are far less important than distinctions within the structure of a given skill which are common to them all (Bartlett, 1958; Fitts, 1964); for example, those between learning and performance, between verbal and non-verbal behaviour, and between the use of input–output connections and input–input associations. The behaviour and learning in a perceptual-motor skill follows the same pattern as that in a cognitive skill, and verbalization, inductive logic and trial-and-error procedures are as common in one as in the other. Different types of skill shade imperceptibly into one another and categorical distinctions are for the convenience of psychologists rather than being based on real attributes of human behaviour.

The appreciation of similarities between skills and the development of general training techniques is hampered by lack of information about perceptual-motor activity. Although Kinetographers (Preston-Dunlop, 1963) have provided many illustrations of movement sequences (in a specialist language), thorough descriptions of skilled behaviour are rare. The next section provides a detailed description of the structure and learning of some simple tracking skills for comparison with the corresponding behaviour in cognitive skills.

Perceptual-motor skills

Tracking is often thought to be the typical example of a perceptual-motor skill, and the pictures of a pilot moving a joystick to maintain a given reading on his altimeter or a driver moving his steering wheel to follow the road are stereotypes of skilled behaviour. However, tracking skills have a peculiarity which is not common to all perceptual-motor skills, in that they can be performed by maintaining a point–point continuous correspondence between stimulus and response. This is the way in which a simple servo performs a tracking task, and human tracking behaviour may be approximated quite closely with a continuous model in some circumstances (Licklider, 1960); for example, when tracking a random course through a system with little lag. However, this is true only for a very restricted choice of tasks, and human motor behaviour is essentially discontinuous and generated by a discrete decision-making process rather than by a continuous correspondence between stimulus and response (Young & Stark, 1965). Even in tracking, where error feedback is available and monitored continuously, the effector sequences are generated discontinuously as complete programmes released when critical configurations of the display are reached. Fig. 10 shows the response (joystick position) of an operator tracking a sinusoidal disturbance through a lagging system. When the position and velocity of the error signal displayed to him attain certain values he changes his control position. The good approximation to the original sinusoidal disturbance may clearly be seen and, of course, virtually cancels this disturbance as the operator intends. An essential distinction between this sequence of appropriate movements in response to visual stimulation by a human controller and a sequence of appropriate replies in response to a heckler by a human debater is perhaps apparent only because we reason in words and not in movements!

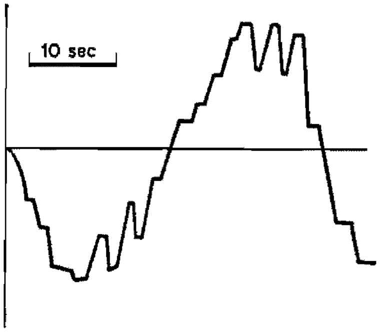

FIG. 10

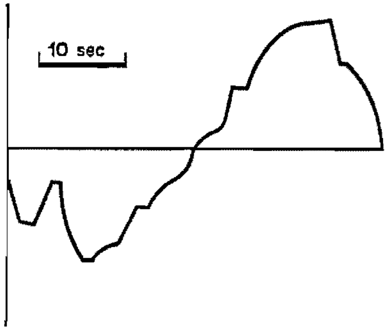

FIG. 11

The decision-making, discontinuous mode of response shown in Fig. 10 is well defined because the operator was at an early stage of learning and the display had a lag which delayed his feedback. Later in learning or through shorter lags the response becomes smoother and less like a staircase because, as shown in Fig. 11, the operator generates shaped movements which more closely cancel the disturbance. It is difficult to see the discrete structure and analyse the growth of these movement patterns, especially as their variety is such that repetition rarely occurs. If however the operator is restricted in his possible output to pushing one of two buttons, then the build-up of action sequences can be closely examined.

The operator is given a push-button in either hand and asked to manipulate them so as to keep a meter needle at the centre of a scale. He is not told what the buttons do but in fact they are arranged to give impulses to the meter needle either to the right or to the left. Whether a particular button gives a right or a left impulse depends on past presses, but they are always in opposition so that a right or left impulse may be obtained at will provided their condition is known. What a particular button will do alternates press by press, so that when a button is pressed another press on it will give the opposite sign of impulse and hence changing to the other button will give the same sign of impulse. The complexity of this control is such that appreciable learning is required of the operator, who first finds it foreign to his normal tendencies and yet simple and natural to use when he has finally learned.

Given these buttons as a control in a simple tracking task the operator rapidly learns what they do, in that he is able to say, for example, that an alternating sequence of presses will send the pointer in one direction and that a sequence of presses on one button will cause the pointer to oscillate without moving far. This verbal behaviour does not enable him to control the display, however, for reasoned responses are too slow and he is unable to overcome certain natural tendencies to make the opposite control movement to that which he would verbally decide. For example, the operator has to commence by pressing one of the buttons to determine their condition. If other disturbances of the pointer do not confound him, then the direction of initial motion is indicative of the state of the buttons. If this motion is in the required direction then a press on the *other* button will continue it, otherwise a press on the same button will cancel it; this strategy is entirely foreign to his natural tendency to change when wrong and repeat when correct.

Whilst this tendency is being overcome, another strategy develops which makes it easier to remember the condition of the buttons: the two buttons are always pressed in sequence, AB or BA, rather than A or B alone as at first. This gives a double impulse in one direction and leaves the system in the same state as it was at the beginning so that further repetitions of AB or BA have the same effect. This strategy further develops into one in which the magnitude of the overall motion is controlled by the length of an ABABAB . . . or BABABA . . . sequence. A complementary strategy forms at the same time which enables the operator to change the direction of motion of the pointer by reversing the button first pushed: ABABAB BA gives a long thrust to the left say which overshoots and is corrected by a short thrust to the right.

Provided he makes no mistakes, the operator is able to control the pointer solely with the strategies already described, but at the start of the task or when he makes an error he has to determine the condition of the buttons. The strategy which develops for this situation is to give two pushes to the same button in quick succession. The direction of initial motion gives the required information, and the buttons are left in their original condition. These strategies and others gradually become integrated, and in the final stages of learning a difficult task the operator produces a continuous stream of button-presses which cannot be assigned to separate strategies. At this stage verbalization is virtually impossible and the operator who earlier in learning could give a fairly coherent account of his approach to the problem is unable to say what he is doing or why.

The previous analysis of a simple tracking situation with visual feedback also applies to the learning of sequences of movements, as in golf, where vision mainly determines the initial timing and nature of the movement. The movement pattern is dominant in golf and visual feedback dominant in simple tracking, but most perceptual-motor skills fall between these extremes.

Perhaps the conclusions of this section are best drawn by asking the reader to call upon his own experience of teaching or learning a cognitive skill, such as Euclidean geometry, and compare it with learning of a perceptual-motor skill as outlined above. Suitable constructions become inseparably attached to certain figures; the steps of a proof combine and amalgamate into unitary acts; two angles may be proved equal and the gathering speed of the pointer may be decreased – if required a sequence of actions is emitted which does either. The analyst's manipulation of an unfamiliar integral and the pilot's manipulation of an unfamiliar aircraft are equally professional, ingrained and based on rules which may have disappeared from consciousness. The problems encountered in training one are similar to those encountered in training the other, and the techniques used in automating the training of one may well be used in automating the training of the other. At present work on training cognitive skills has outpaced that on training perceptual-motor skills, but in future it is hoped that the two will proceed together and provide a comprehensive approach to the universally important problem of making the best use of man's capabilities.

A teaching machine for tracking skills

This section outlines some experiments on the design and construction of a feedback trainer for tracking skills, based on the paradigms of Figs. 8 and 9. The type of environment chosen is related to those of high-performance aircraft, missiles and submarines, which have a dynamic response long compared with that of the operator. The task is to maintain a marker within a given region of the display (meter or oscilloscope) by manipulating a control (joystick or push-buttons).

It is well known that the greater the number of integrators between the control and the display then the more difficult is the operator's task in stabilizing the loop (Ely *et al.*, 1957). With no integrators his control varies the position of the marker; with one it varies the velocity; with two it varies the acceleration (the position of the steering wheel in a car controls the acceleration of the car across the road); and with three it varies the rate of change of acceleration. Since most operators find two integrators controllable but are unable to stabilize three, a triple of integrators in cascade between control and display, together with a repetitive stepwise disturbing signal, has been taken as the basic environment.

The training controller, as shown in Fig. 12, has two outputs from the environment and three inputs into it. One output is the disturbing signal and this enables the training controller to feed in an opposing signal to modify the disturbance in amplitude and frequency; the other output is the velocity of the marker and this enables the controller to feed in opposing signals both to the acceleration and to the rate of change of acceleration. The dynamic characteristics of the environment with these feedback loops are similar to those of the longitudinal motion of an aircraft (Blakelock, 1965), and the strengths of feedback may be said to vary the damping-ratio and natural frequency of the craft. As the former decreases to zero the craft becomes oscillatory, and rapid but smooth control is required; as the latter decreases to zero the craft becomes sluggish, and anticipation is required in its control. The disturbing signal may be taken to represent how much and how often the craft is bumped off course.

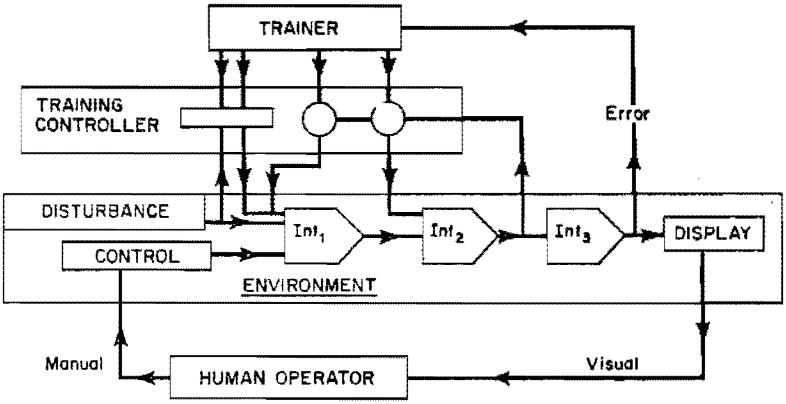

FIG. 12

The trainer compares the magnitude of the error in the display with a fixed tolerance, and increases or decreases the co-operation of the training controller accordingly. Thus, if the loop is stable and the error is small, the amount of co-operation decreases to bring the operator nearer the brink of instability, whereas, if the loop is unstable and the error is large, the amount of co-operation increases until the operator is in control. This strategy enables the trainee to see the effect of his actions, but all the time forces him into regions where there is more to learn.

The parameters used to adjust the co-operation of the training controller determine the net amplitude and frequency of disturbance, and the natural frequency and damping-ratio of the craft. The variation of these four parameters sweeps out a trajectory in five-dimensional testing or training space-time, and for convenience in recording each parameter is either fixed or allowed to co-vary with the others along a single dimension.

Testing

When the machine is to be used for testing, the trainer adjusts one parameter fairly rapidly until the loop is on the brink of instability. It then changes the other parameters either discretely or continuously, maintaining the loop at the brink of instability by adjusting the first. Trajectories in the natural-frequency/damping-ratio plane are of particular interest since Hall (1963) has demonstrated that a pilot's control strategy and his opinion of his craft are radically affected by its co-ordinates in this plane. The boundaries between unstable and stable control in this plane are shown in Fig. 13 for three human operators (A, B, C). They were determined by discretely changing the damping-ratio whilst continuously varying the natural frequency. To check that the trainer is operating correctly, an

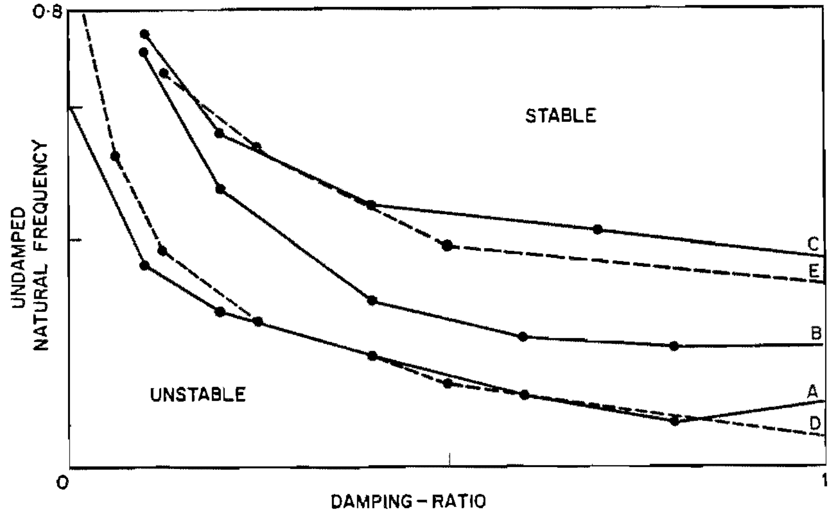

FIG. 13

automatic controller may be substituted for the human operator, and boundaries D and E were obtained from two simple relay servos. A typical deduction from this plot is that operator A must have been detecting the acceleration of the marker as he was able to control the craft at zero damping-ratio.

The manner in which the trainer varies the co-operation to bring both human operators (A, B) and servos (C, D) to asymptotes at the brink of instability is shown in Fig. 14. A measurement of the asymptotic value is possible after less than ninety seconds, and rapid tests under a variety of conditions may be made. These plots show a striking resemblance to those obtained by Gedye (1966) using a teaching machine to test the ability to learn paired associates. This resemblance is more than superficial, for the machine was used as a feedback tester bringing the patients to the brink of an unstable interaction with their problem-solving environment. Increasing the difficulty of a task until the tested object fails is a very sensitive null method, which is used in non-automated forms not only in the Binet and Wechsler intelligence tests, but also in electronic apparatus for measuring the frequency-response of transistors!

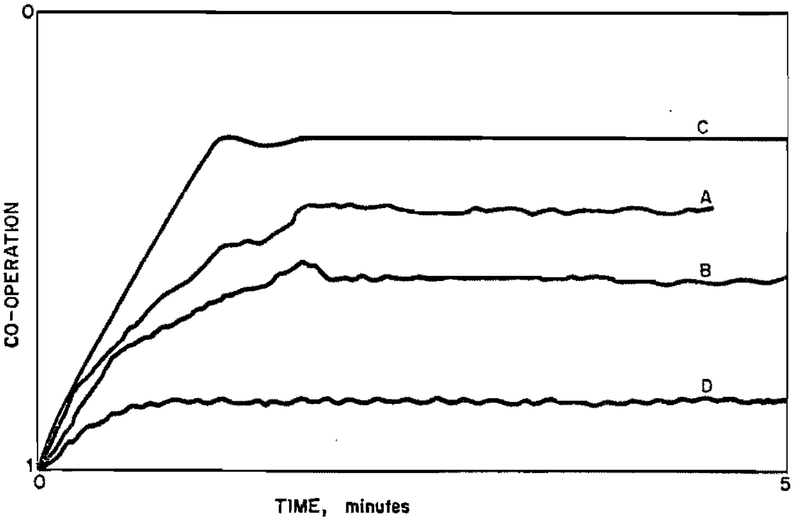

FIG. 14

Training

Training for a task involving one major skill alone induces boredom in the operator, offers little scope for learning, and is unrelated to the perceptual-motor tasks of real life where the integration of many sub-skills forms a major part of the learning. Thus, if the effect of different training techniques are not to be masked, artifacts are not to arise, and the training situation is to have some relevance to reality, a rich situation offering the operator many opportunities to improve his performance by learning and integrating sub-skills is essential. These are the opposite requirements to those for testing innate or previously learned skills, and the tracking task described above with a rolling-ball joystick as control is more suitable for testing than training. However, if the joystick is exchanged for the complex push-button control previously described, then the task is radically changed. The operator has much to learn and there is interaction between his various sub-skills, since it is necessary to know how to use the push-buttons in order to learn about the tracking task, but equally necessary to know something of the tracking task to learn about the push-buttons. Such interdependence is realistic, and makes for a stimulating task which maintains the interest of the trainee.

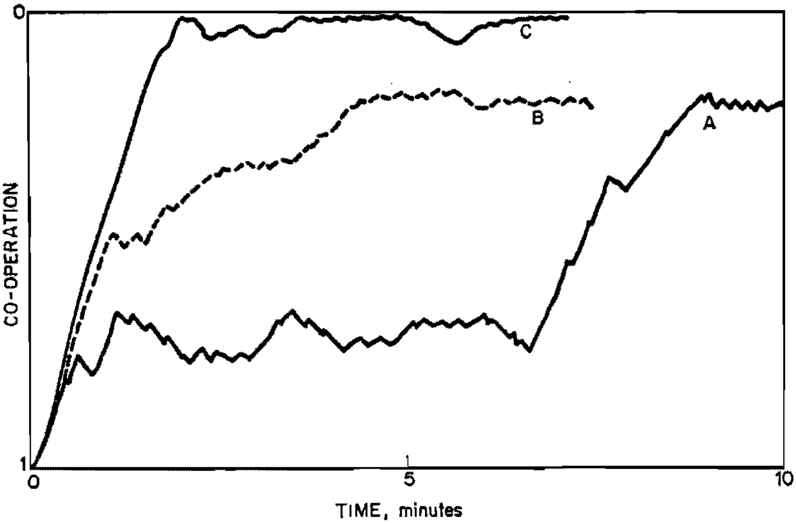

FIG. 15

In Fig. 15, A is the training trajectory of an operator using the push-button control to stabilize a system whose natural frequency and disturbance frequency were fixed, and whose damping-ratio and disturbance amplitude were adjusted to vary the amount of co-operation. The trainer takes him to an asymptote corresponding to his initial ability and maintains him there for five minutes. At the end of this time a sudden increase in his skill occurs and he is taken to a higher asymptote. Trajectory B was generated by the same operator on a second trial some hours later, and it will be seen that his skill is maintained for he goes immediately to the upper asymptote. Such a sudden increase in skill is common in this training situation and corresponds to the learning of some strategy for co-ordinating the push-buttons. C is the trajectory of an operator who has learned the task.

The present series of experiments is designed to compare four training conditions: fixed training where the operator has the required task immediately and has to learn under unstable conditions; open-loop training where co-operation is reduced at a slow, steady rate, independent of the trainee's performance; feedback training where the trainer adjusts the co-operation of the training controller to maintain the loop at the brink of instability; and finally open-loop training where the trajectory generated by one operator under feedback training conditions is used as an open-loop training trajectory for another. This last condition makes it possible to separate the components of training due to a good open-loop strategy and those due to feedback. The subjects for these experiments range from highly trained pilots to patients suffering from major damage to their central nervous system. To investigate the potential of a fully integrated training environment, a teaching machine for cognitive skills is being incorporated so that direct communication is possible between trainer and trainee. This will be used to explain experimental procedure, to study and modify the operator's verbal responses to the tracking situation, and to vary the training situation by linguistic interaction with the trainee.

Summary and conclusions

Whilst the emphasis of this paper is on the training of perceptual-motor skills, the basic theory of automated training is independent of the skill to be trained, and the concepts of complementarity, co-operation/competition and man/machine equivalence may be used in the analysis of any form of interaction between men and machines. Work on machines which adapt and learn has outpaced that on man's psychophysiology, and gives an insight into the problems and techniques of learning which is invaluable to the designer of automated trainers. These machines may also be used as standard operators, since their characteristics, even vagariousness, are repeatable!

Paradigms have been developed for training machines or operators who either learn by example or learn by performing, and these involve a 'trainer' which itself has a control problem. Its strategy in solving this problem is used to distinguish four types of trainer: the fixed trainer which relies entirely on the ability of the trainee to learn the required task; the open-loop trainer which gives a fixed sequence of tasks leading to the required task; the feedback trainer which varies the sequence of tasks according to the trainee's ability; and the adaptive trainer which utilizes its experience of previous trainees to optimize this variation.

Just as Pressey's first teaching machine found its immediate application in testing, so will the first major applications of feedback trainers for perceptual-motor skills be to the testing of abilities in these skills. Whilst the obvious application of such tests is to pilot and driver selection and evaluation, they are also of medical and educational importance. Patients with head and spine injuries show characteristic motor disorders which are difficult to quantify at present, and in an educational context it has been suggested that spatial tests may be important predictors of scientific and technical ability. The feedback trainer described in this paper already provides a rapid, simple and portable test of one type of spatial-motor ability, and the feedback principle can be used in the design of other specific tests.

The expense of flying modern aircraft and missiles is very great and will eventually increase to a level which prohibits training in the air. Sophisticated as they are, present ground-simulators are fixed trainers which rely on human instructors for their long-term feedback and adaption. There are many problems to be solved before feedback can be incorporated in the simulator to make it truly a teaching machine, but pressure for the optimization of ground training is so great that this must eventually be done. The simple trainers described here will find immediate application in flying training to sharpen abilities of motor-response, vigilance and anticipation, and as a means of occupational therapy in hospitals, but the full potential of feedback training awaits realization in future generations of simulators.

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