'Automated Feedback-Trainers for Perceptual-Motor Skills'

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CONTENTS

Section 1.0 Teaching Machines for Perceptual-Motor Skills

1.1 Teaching Machines in Man-Machine Co-operation

1.2 Distinctions between Perceptual-Motor and Cognitive Skills

1.3 Experimental Continua between Skills

1.4 Adaption

Section 2 The Structure of Perceptual-Motor Skills

2.0 Engineering Models

2.1 Performance Measures

2.2 The Detailed Structure of Skilled Behaviour

2.3 Technical Problems

Section 3 Feedback-Trainers

3.0 The Evaluation of Trainers

3.1 Parameters of Difficulty in Tracking Situations

3.2 Measures of the Operator's Relationship to the Task

References

Section 1.0 Teaching Machines for Perceptual-Motor Skills

Although general acceptance of the possible virtues of automated training has enabled effort to be directed to the design of good machines and programs rather than to proof of the utility of teaching machines themselves, research has still been concentrated on the training of cognitive or perceptual skills, leaving perceptual-motor skills largely neglected. Pask [1] built and tested for Solatron a machine for training operators of card-punching machines in which 'cueing', rate of presentation and difficulty of items were varied as a function of the latency and correctness of the subject's responses; eight years ago Stockbridge and Siddall [2] suggested the use of a guided-weapons tracking-trainer in which 'the difficulty of the task is proportional to the success of the subject'; more recently Ziegler, Birmingham and Chernikoff [3] have described a 'teaching machine for the selection and training of operators of higher order vehicles', which removes 'quickening' as the subject's mean error modulus decreases; Large [4] has experimented with Burrows and Jackson's tracking task, comparing performance after a fixed-training-sequence with that after a performance-determined-sequence, and both Elliott Brothers [17] and EMI [18] have demonstrated self-adjusting trainers.

This work however has been negligible compared with that on machines for teaching cognitive skills, probably because of lack of data on the structure of perceptual-motor skills themselves and the technological difficulties of building this type of automatic trainer. It is unlikely to be a matter of relative priorities since automated trainers for perceptual-motor skills would not only have important military applications in enabling rapid mobilization of reserves for instance, but could also give a more fluid structure to the pool of industrial workers, reducing the hardship of redundancy and aiding the trend towards skilled and semi-skilled workers; in medicine also they could alleviate the shortage of trained staff for the rehabilitation of the injured.

1.1 Teaching Machines in Man-Machine Co-operation

Since in perceptual-motor skills the human controller is often operating on complex plant through machinery with far more logical power than any teaching-

machine yet conceived it is worth examining automated training within the wider framwork of man-machine interaction and cc . peration to realize the peculiar relevant of the teaching-machine to modern trends in automatic control theory.

Teaching-machines in general have already been used other than in training, as tests of ability, for example, and as guides through a logically complex task. The rate of progress through a program, the ultimate level reached, the path through a branching program and the responses made, all in some way act as indicators of individual differences and abilities. Also the machine may be used not to instruct or test but as a decision mechanism guiding the operator through a complex task. In this latter application the human operator is virtually a transducer whose pattern-recognition and motor skills are exploited, and the man-plus-machine acting together bear the same relationship to the task as does the teaching-machine to its pupil in normal practice; this equivalence of relationships is very relevant to the theory of automated training.

All three applications may be combined in a system which instructs the human in some aspects of a task so that eventually they are loaded solely upon him, guides him where complex chains of logical operations or high storage-capacity are required, and all the time tests his level of ability so as to direct its own program of instruction and guidance. At a simple level the machine of Newman and Scantlebury [6] is capable of performing all these functions and has been used for both teaching and guidance, and Smallwood [7] has experimented with a more complex machine using a digital computer which is adaptive also.

Within the wider framework of man-machine co-operation the direction of flow of responsibility may well be reversed and the r.,n 'train' the machine rather than vice versa. There are many tasks at present performed by humans which it is desirable to automate but which are beyond our present ability to do so, and machines which through close examination of how the human performs the task acquire this ability themselves have

been suggested. The future concept of man-machine relationships will not be narrowly confined to training and control but one of close man-machine co-operation with continually shifting responsibility. Automated trainers are thus only a peculiar aspect of this relationship and may well find their main application as part of a more comprehensive system.

1.2 The Distinctions between Perceptual-Motor and Cognitive Skills

So far the close relationship between all forms of automated trainer, whether for cognitive, perceptual or perceptual-motor skills has been emphasized, however it is obvious that there are great differences between perceptual-motor and cognitive skills which make the design-problems for trainers somewhat different. That this difference is not immense may be seen in Bartlett's [8] analysis of cognition as a 'high-level skill'.

Perceptual-motor skills are distinguished from cognitive skills by two main features:-

1. Perceptual-motor skills are externally paced and the operator is essentially on-line with his time-scale determined by the controlled plant.

2. Perceptual-motor skills cannot generally be verbalized and hence introspective analysis is misleading if not impossible.

These are differences of degree rather than absolutes. There are linguistic skills such as debate where the operator is to a great extent externally paced and there are motor-skills such as Fitts' reciprocal tapping task where ballistic movements are only a minor aspect of a skill. There are also cognitive skills which are not verbalizable - a mathematical analyst may be able to suggest approaches to a problem without being able to say what features of the latter suggest these approaches. And there are skills, especially those upon musical instruments, which have been analysed in great detail.

These differences do exist however and both help and hinder the designer of automated trainers for perceptual-motor as opposed to cognitive skills. In convential programs the subject is self-pacing, taking as much time as he required over each item in the training sequence; this being considered

a great virtue of the individual instruction allowed by teaching-machines. In perceptual-motor skills however the locking of internal pacing to external pacing is a major factor in the skill, and a simple stimulus-response-reinforcement structure in which time is under the control of the subject in magnitude if not direction is no longer viable - time must be considered a causal variable in perceptual-motor skills.

The weak dependence of the majority of perceptual-motor skills on verbal processes is in one way a great advantage since the latter do not yet have even the semblance of being understood, whereas perception, motor-activity and decision-making have at least the beginnings of powerful theories tied closely to experimental fact. Equally however this lack of verbalization takes from the programmer a major source of information on the skill to be taught - his own experience and the analysis of others. The foundation of teaching-machine practice is built largely on self-analysis, pragmatism and extrapolation of behavioural theories from animals to man. The latter remain for the worker on perceptual-motor skills but the former is a sad loss.

These differences at a practical level must not obscure the close relationship between design problems at a more abstract level. Deciding in a linear program on the next item, which must lead in the right direction and be closely related to the previous yet slightly more difficult, is very similar to deciding how to change a tracking task almost imperceptibly so that it is essentially the same task and yet more difficult, and in both cases the sequence of changes must be such that the operator is drawn from an easy initial task to the demanded final task.

Similarly in a branching program decisions must be made based on the pupil's past performance as to what part of the program is to be taken next, and in more complex adaptive programs a model may be formed of the pupil on which to base decision procedures. It is at this level that the designer of machines for training perceptual-motor skills has some advantage, since it is often easier to obtain a performance measure in tracking than in a verbal skill, and generally far easier to form a model of the human controller than of the human thinker.

1.3 Experimental Continua Between Skills

It would be possible to develop experimentally the concept of perceptual-motor skills as non-verbalizable, externally-paced analogues of cognitive skills by building a continuum of tasks which at one extreme are obviously 'cognitive' and at the other 'perceptual-motor'. Such an exercise would not only unify work on automated training and make clear the distinctions between skills, but also enable relationships to be established between individual abilities and performances on seemingly very different tasks. It is an essential feature of human behaviour that it is manifested in a very wide range of environments and restriction to one can be very misleading. Fleishman[9] has contributed much to the analysis of inter-relationships between perceptual-motor skills, but there has been little work on relationships between skills in general.

An immediate practical use for this data in automated training would be to predict the operator's initial ability and ultimate performance at the demanded task, and thus enable training parameters to be adjusted to suit the individual. In truly adaptive trainers the tests would be carried out within the training sequence itself, probably as secondary-loading tasks. Initial performance at the main task is no indicator of ability[10] and tasks which give useful information to a trainer may seemingly be far removed from those which are to be taught.

1.4 Adaption

Teaching machines for all skills are devices which rely on the adaption of the human operator, attempting to control the modification of his strategy with experience and maximize its desired effect. Although adaption is gaining increasing attention from control-engineers[11] and biologists[12] alike, there is as yet no generally accepted definition[13] and even that by extension is hotly debated.[14] The essence of the phenomenon is however that an adaptive controller reacts to the same situation in different ways

dependent on past experience, and generally, but not necessarily in such a way as to improve its performance in that situation. (15)

The course of adaption is not necessarily fixed but may itself depend on the controller's past experience, and thus feedback-trainers which change the environment of the controller according to measurements of its state have inherent advantages over open-loop trainers which allow autonomous adaption to a fixed training-sequence. Such trainers are themselves controllers operating upon the adaption-automaton of the trainee to take it to a demanded final state, and their design encounters those problems of state-determination, demand-determination and policy-optimization which arise in the general control problem. (16) The control of human-adaption and the control of industrial processes are esentially similar problems and the study of either may throw light on both.

Section 2 The Structure of Perceptual-Motor Skills

2.0 Engineering Models

The human being is a controller of particular importance in aviation where ultimate responsibility for a plane in flight still resides with its human pilot, and a great deal of time and effort has been expended by the industry on attempts to describe the human controller in engineering terms so that he may be analysed as a control component.[19] Naturally these terms have been those most fully studied in classical automatic control and it is fortunate that within the restricted range of situations encountered in the simulator a linear model shows a good fit to the behaviour of the human pilot, as linear systems form the backbone of control theory.

Although cybernetically the close fit of a linear model to human control behaviour is completely satisfactory, it has very little relevance to the psychology of that behaviour except in so far as it poses the question of why the nonlinear, adaptive, discontinuous human controller has such an apt description in seemingly contrary terms, and demands that any other model should have the same linear approximation in similar circumstances.

A linear model of the trainee might be useful information for an automatic trainer, but it is unlikely that the state-description thus obtained would be much better than those based on performance-measures technically far simpler to obtain. The linear describing function is essentially a statistic of the operator's reaction to a particular environment rather than an ontogenic parameter or a description of his behaviour. It is possible to extract it only through the analysis of a period of tracking far longer than the adaption-time of the operator and thus it has an inherent lag.[20] The remnant term which cannot be fitted by a linear model is generally small under a rms error criterion and this is the basis of the claims of a good fit, but mean error functionals are notoriously soft, having little variation over a range of sub-optimal models,[21] and the linear transfer function is probably much more a property of the environment than a state-description of the

operator. It may be shown that some data-sampling, bang-bang models of the human controller have linear approximations giving transport-lag and velocity-feedback terms of the right magnitude, but there have been no control experiments to examine such pseudo-linearity

One possible use of describing function data is suggested by the work of Hall [22] who found that pilot opinion of simulated aircraft correlates adversely with the relative magnitude of the remnant term; hence this might be used as a measure of task difficulty. Development of special-purpose computers has made it feasible to measure describing functions on-line, [23] [24] but the value of these statistics as indicators of the state of the operator has yet to be shown.

There have recently been attempts to model the human-controller by data-sampling servo-mechanisms, such as that of Bekey [25] for visual-motor tracking or that of Young [26] for eye tracking-movements. Unfortunately the former especially is another example of the irrelevance to psychology of this approach - the few experiments were at a statistical level where differences between continuous and sampling models are negligible. Bekey's work is immensely interesting it adds nothing to our knowledge of skills. Indeed experimental data is remarkably scarce in a field where so much effort has been expended, and that which exists is often obscured by a priori theoretical analysis.

Although advances in modelling the structure of human control strategy cannot be expected unless concurrent with detailed analysis of human behaviour in skilled tasks, there is sufficient experimental evidence to suggest that apt models will be found in free-running, externally-synchronized, time-discrete systems with both visual and kinesthetic feedback and more than one adaptive loop. These non-linear, discontinuous, non-stationary systems are not necessarily more difficult to analyse, and certainly easier to synthesize, than quasi-linear, adaptive systems, and follow trends in automatic control theory itself

towards the use of more powerful systems than linear vector spaces,[26] such as topologized automata,[27] which will eradicate many of the obscurities inherent in such terms as 'quasi-linearity'.[16]

There already exist examples of synthetic complex, non-linear controllers, such as the 'learning-machines' of Newell, Simon and Shaw[29] and of Andreae[30], which when set tasks similar to those performed by human beings show a level of ability not always markedly less, and comparison of their complexity of behaviour with that of the human is not trivial.[31] To use these machines as models of human behaviour would be foolish, but it may well be that this type of controller, with adaptive perceptual and motor processes and adaptive decision-making, is an example of the form which realistic models will take.

2.1 Performance Measures

Another source of data on human perceptual-motor skills is the multitude of papers on the variation of performance measures with task parameters in control situations. Unfortunately the arbitrary functionals of error used as performance measures are difficult to interpret and strongly dependent directly upon the task rather than upon the subject's relationship to it. Magdaleno and Wolkovitch[21] have shown the softness of error-functionals in the evaluation of control systems - 'the mean square error of a wide variety of off-optimum systems is little higher than that of the optimum'; Shelley[32] has shown that different performance measures give very different rank orderings of the same tasks; and as a light-hearted gesture Taylor and Birmingham[33] have performed an experiment which ought long ago to have been a standard control in evaluating human 'learning-curves' - that of synthesising a simple controller for the system and plotting its 'learning-curve' as a variation of its performance with changes in its parameters.

The defects of error-functionals as measures of task difficulty are much less evident in recent use of performance at 'loading-tasks' as indicators of the operator's 'spare capacity' and physiological variables as indicators of his level of arousal. Whether the justification of secondary-loading techniques in terms of information-theoretical models of the human controller is valid or not, they have already proved to have far greater sensitivity in assessing task-difficulty than performance-measures based on error in the main task.(34) As the operator adapts and functionals of the latter reach their asymptotic minimum performance on secondary tasks is still improving, showing that the operator is increasing the efficiency with which he implements his control strategy even though he cannot improve upon it.

Loading tasks need not be entirely separate from the main task and indeed some aspect of this latter may be used as loading provided it is of secondary importance to the operator, however loading must be such as to permit and distinguish a wide range of performances. Tasks varying from audio 'shadowing' (35) and mental arithmetic (36) to simple and multiple-choice responses to tones or lights (37) have been used, and lack of standardization is a major difficulty in comparing experiments. The continuum of tasks ranging from cognitive to perceptual-motor discussed in section 1.3 may provide standard loading-tasks capable of meaningful comparison.

The activity of the sweat glands as measured by GSR has long been known as an indicator of anxiety or arousal under stress and more recently irrelevant muscle activity measured by EMG has been shown to have similar properties.(38) If the operator's anxiety or level of arousal is correlated with the difficulty of the task then these physiological measures might be used by trainer as indicators of his relation to the task. Work at the Road Research Laboratory (39) suggests that drivers of cars tend to drive in such a way that their GSR remains constant, and this may be a useful criterion for adjusting task difficulty in training. At the Institute of Aviation Medicine (40)

recent experiments have shown that both secondary loading and a wide range of physiological variables such as GSR, EMG, respiration-rate and volume may be used to order altimeters as sources of difficulty in tracking although performance at the main task does not appreciably vary, and such a battery of physiological tests, loading tasks and performance measures may be necessary to give adequate indication to a trainer of the operator's state.

2.2 The Detailed Structure of Skilled Behaviour

The most thorough work on the psychological structure of skilled behaviour has been a detailed analysis of some very simple perceptual-motor skills, such as Welford's determination of reaction-time to contiguous stimuli as a function of their temporal spacing and the descriptions of Wilde & Wescott and Crossman & Goodeve of movements in response to step-demands. This work has not been extensive enough to model the integration of these part-skills into a complex whole, but it exemplifies the exhaustive analysis of skilled behaviour which must be performed in order to set up realistic models of the structure of perceptual-motor skills.

The main phenomena established are briefly:-

1/ Perceptual-motor response-times show a high variance which cannot be eliminated by improvements in experimental technique.

2/ Reaction-times to contiguous stimuli show variation with their temporal spacing, which may be ascribed to a 'refractory period' following a a reaction,[41] but equally to a data-sampling perceptual process.

3/ Reaction-times to the cessation of repeated stimuli show a discontinuity at stimulus-repetition rates of about 10cs,[42] which could be ascribed to a synchronizable, time-discrete perceptual-motor process.

4/ Simple and multiple-choice reaction-times over an ensemble of subjects show strong regression upon their alpha-periods prior to reaction,[43]

suggesting that cortical activity reflects the timing of an internal decision-mechanism.

5/ Movements of the arm in response to step-demands show bang-bang control with distinct velocity-triangles at least 180 msec in base,[44] suggesting that movements are generated by time-discrete, optimal command-sequences.

6/ There is kinesthetic feedback of force but not displacement,[45] and the internal feedback signals are monitored as stimuli showing the effect of 3/.

7/ The human controller adapts in about 400 msec to unexpected control reversals, and there is almost complete transfer to the opposite motion.[46] [47] Unexpected changes in gain or lag are compensated over a longer period.[45]

8/ A recent classification of a set of simple skills based on ease of lateral transfer as assessed by self-rating shows that open-loop tasks, in which adaptive feedback to the control-strategy is delayed, form a separate cluster from closed-loop tasks, in which feedback is continuous.[48] This distinction suggests that mechanisms independent in their asymetry subserve the functions of adaption and control.

These phenomena suggest that behaviour in tracking is generated by a time-discrete, bang-bang, adaptive control-process, but many further experiments and much replication will be required before this can be modelled.

2.3 Technical Problems

The examination of skilled behaviour in tracking has long been a technical rather than psychological problem. Even in such simple cognitive skills as paired-associate-learning human behaviour is probably far more complex than any during tracking, yet the former, because of the ease with which data may be collected and analysed have received much more detailed study, whilst the latter have been analysed mainly at a smeared-out, statistical level. A few workers (Section 2) have looked at the

details of simple tracking movements by analysis of pen-records, but this technique is arduous and would make comprehensive analysis of perceptual-motor skills a lifetime's work.

Both the realization of automatic trainers and the performance of crucial experiments on adaption require that the analysis of tracking data be automated and on-line. Only in this way can data on the trainee or subject's behaviour be fed-back to alter the course of training or experimentation. Fortunately modern data tape-recorders and analogue and digital computing techniques make such analysis feasible, though detection of such features as 'velocity-triangles' may require the more sophisticated techniques now being developed for automatic pattern-recognition.

Section 3 Feedback Trainers

3.0 Evaluation of Trainers

Our present knowledge of perceptual-motor skills is not sufficient to enable theoretical development and anlysis of feedback trainers, and the immediate approach to automated-training must be through empirical comparisons of simple training schemes. In practice however the experiments involved in such comparisons will not only give a pragmatic evaluation of the schemes themselves, but also supply a wealth of data on human skilled behaviour and its adaption, the analysis of which will contribute greatly to our basic knowledge of skills.

The evaluation of feedback-trainers requires not only an experimental measure of the efficiacy of training, but also a standard against which they may be judged. The obvious theoretical standard is the optimal open-loop trainer, but in practice not only is this unknown but also likely to be more complex than an equivalent feedback trainer - the trade-off of feedback for complexity is a universal phenomenon. Another standard of the same type would be established training procedures, but in practice these are prolonged introductions not to a single task but to a unitary system of interdependent tasks; although some aspects of simulated flying might be used. Rather than attempt to answer questions as to whether the feedbakc-trainer is better than the optimal open-loop trainer, or better than established training-procedures, it seems better initially to ask whether the feedback in itself has any effect at all. This question could be answered by comparison of an operator trained by an on-line feedback-trainer with another operator trained on the same task sequence.

It is unfortunate that as skills are very well retained subjects cannot be used as their own controls, and if matched pairs are used then measures of individual differences may be crucial in factoring out interference with the main phenomenon. Homogeneous groups of well-documented subjects would

obviously be of great advantage.

The measure of efficacy of training is not methodologically so important, but should be sensitive to the effects of training and also reflect the ultimate purpose of the trainer. Performance at the main task, retention, efficiency of strategy as measured by loading, and robustness of performance under stress are important qualifications of well-trained personnel, and will all require testing if feedback-training is to be properly evaluated.

3.1 Parameters of Difficulty in Tracking Situations

Simple feedback-trainers required both a task which may be continuously varied in 'difficulty', and also some measure of the operator's relationship to the task which may be used to vary the 'difficulty'. Empirical testing of trainers will have no practical value unless the results can be generalized to a number of real-life situations, and thus it is desirable to investigate a comprehensive set of parameters of difficulty which reflect as many aspects of a control-situation as possible.

A tracking situation may be split into plant, demand, control and display components, and examples are given of parameters of difficulty within each component:-

1. The Demand Function The operator is required to follow a course which is generally a time-dependent analogue variable and in real-life would be generated by a winding road or evading target. Demand functions are more difficult to follow the greater their peak amplitude, high frequency components and unpredictability.

2. The Plant Dynamics The command-signal generated by the operator is converted by the controlled system into an output which has to be matched to the demand. Physical systems such as submarines or aeroplances may be unstable, nonlinear or lag in their response. Instability, lags of high-order systems and non-linearities such as dead-space increase tracking difficulty.

3. The Physical Dynamics of the Control The operator is coupled in to the plant by a physical system in contact with his limbs, such as a joystick or steering-wheel, and these may required a high-force, large movements or have backlash, all factors increasing tracking-difficulty.

4. The Display The error in matching plant output to demand may be displayed to the operator either as a pursuit or compensatory display and this may itself lag, be spatially incompatible with the control, or be difficult to perceive through intermittency or the presence of similar extraneous signals. These phenomena are especially important in the blind navigation of vehicles by instruments and radar, and cause difficulty in tracking.

3.2 Measures of the Operator's Relationship to the Task

Although error-functionals are of little use in comparing controllers since they do not have a wide enough range of variation, when used as feedback to vary task-difficulty so that a functional value is kept at mid-range this criticism is no longer valid and such a strategy may well be useful in training. Equally performance at loading-tasks or physiological measures of stress may be used as feedback, and hybrid criteria setting acceptable levels and priorities for several variables may ultimately be used.

The feedback-trainer need not be completely automated initially but could partly be the experimenter who, given certain performance measures, a parameter of difficulty to manipulate and perhaps some informal 'rules of adjustment', could attempt to act as an optimum trainer. In this way more information might be gained than through initial crude attempts to automate the whole training process.

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