THE HUMAN OPERATOR IN MAN-MACHINE SYSTEMS

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ABSTRACT

Man as an operator of machines has been a subject of study from three different angles: Engineering, Physiology and Applied Experimental Psychology. The different approaches of workers belonging to these three different branches of science have been briefly discussed in this article. The importance of studying the human operator, as a whole, in a generalised man-machine system has been pointed out.

Introduction

Man as an operator of machines has become a subject for serious study since the last world war. Evidence on the characteristics of the human operator in man-machine systems has been accumulating chiefly through three sources—Engineering, Physiology and Applied Experimental Psychology. These three branches of science indicate different approaches to the study of human operator. The primary interest of the engineer lies in the study of man as a mechanical operator. The physiologists on the other hand, are mainly concerned with the neuro-muscular composition of man and his suitability for the work of operation of machines from that standpoint. While the engineer considers man as part of a servo-system or as a servo-mechanism itself, to the physiologist man is a bundle of nerves and muscles, usually reacting in specified ways to stimuli that come from outside. The psychologist's approach to the study of the human operator, on the other hand, is a humanistic one. The human operator is studied in all his completeness. He is not studied in an isolated situation, but against the background of a variety of factors which determine his efficiency at a particular task. Before going on to describe further the psychological factors affecting the human operator in man-machine systems, it is appropriate to state briefly a few relevant observations of engineers and physiologists on this subject.

Man as a Servo-mechanism

The first systematic study of the human operator from the engineering point of view was, perhaps, that of Craik[1]. He suggested that the human operator in a control system can be compared to a servo-mechanism. According to him man may be regarded as a chain consisting of the following items:

"(1) Sensory devices, which transform a misalinement between sight and target into suitable physiological counterparts, such as patterns of nerve impulses, just as a radar receiver transforms misalinement into an error-voltage.

(2) A computing system which responds to the misalinement input by giving a neural response calculated, on the basis of previous experience, to be appropriate to reduce the misalinement; this process seems to occur in the cortex of the brain.

(3) An amplifying system—the motor nerve endings and the muscles—in which a minute amount of energy (the impulses in the motor nerves) controls the liberation of much greater amounts of energy in the muscles, which thus perform mechanical work.

(4) Mechanical linkages (the pivot and lever systems of the limbs) whereby muscular work produces externally observable effects, such as laying a gun."

The second important contribution made by Craik is his theory of intermittency of human operation in control systems. From a study of some laboratory experiments in experimental psychology carried out at Cambridge, Craik formulated the theory that the human operator behaves as an intermittent correcting servo-mechanism in control systems. That is, the response of the operator to a continuous input of stimuli is not itself continuous, but intermittent. Further the movements executed by the operator are ballistic in nature. Sufficient evidence for this theory of intermittency of human control action is not observed in ordinary tracking situations as there are other factors like inertia and perceptual anticipation which are also operating, tending to make performance smooth and uniform. Hence, in actual practice, this theory does not appear to be a very useful one. Besides, the concept of psychological refractory phase on which this theory is based has come up for criticism in recent times. Notwithstanding this, Craik's suggestion regarding the essential similarity between the human operator and servo-mechanisms in control situations has stood the test of time and has been, on the whole, a very helpful concept.

Further elaboration of this concept took place subsequently. Hick and Bates[2] in their monograph entitled "The Human Operator of Control Mechanisms", made a comprehensive survey of much of the information that was available on this subject, with a view to provide some useful hints to engineers engaged in constructing machines. The various psycho-physiological factors involved in the operation of control mechanisms were carefully analysed and the analogy between the human operator and servo-systems established. Among the various psycho-physiological factors mention is made about thresholds, sensory feed-backs, reaction time and the psychological refractory phase. On the motor side, the subjects discussed were motor coordination, the ballistic nature of the muscular movements in control tasks, optimum rates of work, and accuracy in executing movements and application of force. After making a clear exposition of the psycho-physiological background, the authors go into the question of the operation of the various orders of control systems. To start with six different types of control systems (given here in increasing order of complexity) were identified: Positional control, Velocity or rate control, Rate-aided control, Acceleration control, Regenerative control and Aided display control. The criteria of performance and stability were used in judging the relative merits of these types of control systems. Generally speaking, it is desirable for a control to be of as low an order as possible. The question of suitability of a particular type of control system for a particular type of operation is, of course, bound up with a number of other practical considerations.

Analysis of Tracking Performance

An exhaustive analysis of tracking operation was undertaken by Tustin[3]. His bjective was to establish an approximate linear law for the human operator.

He, however, did not appear to have succeeded in this on account of certain inherent non-linearities in the operator's behaviour, such as thresholds and intermittency. As Hick and Bates[2a] observe, "It seems probable that the linear continuous treatments cannot take us much further in the search for a representation of the human operator. As we have said, they may often emphasize those properties of the mechanism or the task in general which are likely to give particular difficulty to the operator; they may even indicate roughly the optimum values of certain of the parameters, but it would be unwise to rely upon them for that."

North tried a different approach, which according to Hick and Bates, appeared to be promising. The essence of North's approach is that, in studying tracking performance, we are looking at a system which is subject to fluctuations of an unpredictable or random nature, and which can therefore, be described in terms of probability distributions. The type of equation which North believes would fulfil the requirements is the linear finite difference equation with constant coefficients. A difference and not a differential equation is necessary on account of the random variations, which can not be dealt with except in the form of successive discrete values.

Without going into the mathematicalities of these different approaches to the study of the human operator, it should be pointed out here that these equations have been derived mostly from input and output data in specific tracking situations and hence they lack universality in application. Even if the linear equations could be suitably amended to take in a few more factors like thresholds, and the intermittency, we are still not saying much about the human operator in man-machine systems in general. Most of the human operations are much more complicated than tracking. Those operations which are expressible by linear equations are perhaps better performed by machines than by men. Such operations are, in fact, fast going out of human hands.

The Sensory Motor Make-up of Man

Fundamentally, the human being may be looked upon as a complex organization of a large number of individual sensory (input) and motor (output) elements. The nervous system which is the medium through which messages pass from the receptor (sensory) to the effector (motor) organs, consists of a vast network of nerve fibres. Within the nervous system there are innumerable negative feed-back pathways which are highly important in manipulation of controls. The interconnection between sensory and motor elements may be inherited or acquired through the process of learning. Inherited reactions, which take place with lags of the order of a few milliseconds only, are called reflexes. Most of the acquired reactions take enormously more time than the reflexes. The time lag between input and output in a simple key pressing task is about 0·2 sec. which is known as the simple reaction time. Reaction time varies from one sensory modality to another and also from one type of motor activity to another. The significance of reaction time lies in the fact that in many control situations it sets a definite limit to performance. There is some indirect evidence that the reaction time in continuous tracking is of the order of 0·3 to 0·35 sec. The exact reasons for time lags of this type are not clearly known. 'The reaction time, though to a small extent due to the time of transmission of nerve impulses from sense organs to brain and from brain to muscle, is chiefly the time occupied by the process of analysis and selection in the brain, about which next to nothing is known"[2b]

A second limiting factor in human control operation is what is known as the threshold for excitation of a sensory organ. The threshold is commonly taken to be the magnitude of a stimulus which is just perceived. Responses can be evoked only to supra-threshold stimuli. This type of threshold is known as the 'absolute' threshold. There is a second type of threshold which is known as the 'differential' threshold. The differential threshold is the minimum perceptible difference between stimuli of two different magnitudes. The importance of these thresholds lies in the fact that the human operator in a control system can react to an input stimulus only if it is above the threshold value. In a tracking situation, for example, the misalinement must be sufficiently great as to be perceived before the operator can move his controls to reduce it.

Subject to the abovementioned limitations, the human operator by and large, behaves in a mechanical fashion, matching his output to the input stimuli he receives. Manual tracking, for example, is considered a particular form of serial reaction task, in which stimuli occurring in close succession are responded to mechanically by the operator. In such a situation as one of following a moving target e.g. an aeroplane with a gun-sight, the man, the control mechanism and the gun sight are linked together in a closed circuit and the human operator behaves more or less mechanically. The only factors which need to be studied in this connection are the sensory capacities, the thresholds, the reaction time and the capacity for muscular output. Besides these, the fundamental properties of a closed circuit system such as stability, natural frequencies, and steady state behaviour also appear to merit attention.

One fact stands out clearly from the foregoing, namely, that the study of human operator from the mechanistic view point has been till now mainly restricted to one type of operation-manual tracking. The larger aspect of the human operator in a man-machine system in general does not appear to have received sufficient attention at the hands of engineers, even though the gap appears to have been filled to some extent by psychologists.

Human Skill in Man-machine Systems

It is a recognised principle that the overall efficiency of a man-machine system depends both on the man and the machine. Here we are concerned mainly with the characteristics of the human operator in so far as they affect the operation of machines. Machine operation usually involves some degree of skill. There are some machines which call for a highly developed skill and some which can be handled after relatively little effort. The one outstanding feature of any form of skill is the consistent timing of successive steps or moves in an operation. The operator looks out for signals from the machine and reacts to them by moving the controls appropriately. These are the two essential factors in any type of skilled operation. The efficiency of the operator depends partly on how the display of information is arranged for him and secondly how the movements which he is capable of making can most effectively be adopted to run the machine efficiently. All machine operations, in the last analysis, can be regarded as interplay between display and control. A display can be so designed as to make it very difficult for any ordinary human being to interpret it. Similarly a control may be placed in an inconvenient position or may be made inaccessible or otherwise difficult to operate. The result is the skill of the operator suffers. As Professor Bartlett says "there is nothing else so conducive to skill fatigue as the accumulation of a number of small difficulties no one of which by itself, perhaps is particularly troublesome to deal with. It is a cardinal rule of design to attempt to find those arrangements of display and control which most operators can learn in the shortest time"[4]. It should be noted here, however, that the terms display and control are used to cover all effective working conditions.

Fatigue—Much of the fundamental work on the conditions affecting human skill in operation of machines was done at the Cambridge University. Some of the important factors that were investigated are: fatigue, boredom, environmental stress, speed and load stress etc. Wartime experience naturally gave priority to the study of the problem of fatigue in operators. The now wellknown work of Davis and others[6] on the 'Cambridge cockpit', though primarily intended to study fatigue in aircraft pilots, has thrown considerable light on the effects of over work generally on skilled performance. The Cambridge studies demonstrated that "the characteristic changes which take place in skilled human performance with long continued exercise are very different from those which normally mark the continuation by repetition of isolated muscular or mental activity "[5]. The following are usually regarded as the early signs of skill fatigue:

(*i*) A tendency to require bigger than normal stimuli changes in the display situation before action is produced.

(*ii*) Inaccurate timing of movements leading to a loss of smoothness in operation.

(*iii*) Retraction of normal span of anticipation, resulting in lagging behind in executing movements.

(*iv*) Narrowing down of the span of attention leading to overconcentration on one aspect of the display to the neglect of the others.

The tired operator tends to make more movements than the fresh one does. He does not grade the movements properly nor does he time them accurately. He is not able to react any longer in a smooth and economical manner to complex patterns of signals. His standard of performance falls without his becoming aware of it. The ultimate result of all these changes is a fall in efficiency in whatever operation he may be engaged.

Boredom—The second important outcome of the Cambridge experiments is the concept of boredom. In some man-machine systems the operator takes on the job of waiting for signals for action or monitoring some equipment which may need his attention occasionally. In situations like these, the operator has to be alert continuously even though he may not receive any signal for action for hours on end. It is easy to imagine how bored one gets in such a situation. The result is the efficiency of the operator goes down with time, just as it happens in the case of fatigue. To avoid this kind of sagging in performance it is necessary, if possible to arrange the work in such a fashion that the operator has enough to do all the while and does not have to sit and wait for something to happen.

Environmental stress—The problem of environmental stress as it affects human performance is an equally important one. It is well known that there are definite limits to environmental conditions within which man feels comfortable and outside of which he becomes easily exhausted, feels discomfort and suffers fall in performance. The result is the same whether we are investigating the effects of extreme heat on man, or extreme cold or the effects of noise. The ultimate result is always a fall in performance in the long run. The human being has remarkable capacity to adopt himself to any type of environmental conditions; but this he does often at the cost of highly increased effort. It has been experimentally observed that the normal level of performance, even though it may show a transitory upward trend in the initial stages of the imposition of an environmental stress, cannot be maintained for long. Incidents of dramatic breakdown in performance were common place during wartime when work had to be put in for long hours in uncongenial environmental conditions.

Speed and Load—The fourth factor is the effect of speed and load of work on performance. If the skill in any machine operation is not to suffer, then the speed at which the operator receives signals for action should not be excessively high or low. To quote Prof. Bartlett, "if the overall speed is increased or decreased beyond the limits that are consistent with smoothly timed succession of response, the adverse effect piles up at a disproportionately rapid rate with every further increase or decrease"[5]. Load depends on the number and arrangement of distinguishable signals, which have to be dealt with simultaneously or in rapid succession. To put the whole thing in a more simpler form, to be successful at any kind of machine operation, there should not be too many factors demanding attention at the same time and secondly these factors should be spaced out in time such that the operator can cope with them sufficiently well. If the operator is either required to do too many things at the same time or he is required to perform the same or different operations at a very fast rate, he is bound to breakdown under what is technically known as the resultant "Load and Speed Stress". These are some of the important factors in human operations which have come to light during the investigations.

Human Engineering

Considerable research has gone into the study of the various physiological and psychological limitations in man as they affect his role as an operator of machines. Keeping in view these limitations, conditions were laid down regarding the design of equipment. Much of the equipment that was in use early in the last world war, was not very suitable for use by the ordinary human operator. Special skill and effort were needed to operate them. Many machines were so highly complicated to operate that only few could be found to possess the required skill. It took a long time to realise the futility of selecting fewer and fewer people who were equipped to perform the more and more complex tasks. It became obvious that the tasks had to be simplified. A realisation of this led to the establishment of the science of Human Engineering. Briefly, Human Engineering means engineering for human use. The aim of Human Engineering is to design equipment in accordance with operator characteristics so that when an operator uses, maintains or monitors that equipment, he does it with a maximum of efficiency and a minimum of error, Successful design of equipment for human use requires consideration of the basic human characteristics-sensory and motor capacities, intellectual abilities, common skills, body dimensions and in addition environmental effects on human performance.

Man as a Monitor of Machines—One of the modern trends in weapons systems development which is of special concern to Human engineers is to make the systems as automatic as possible but still retain the human as a monitor. To quote a recent writer on Human Engineering "one of the activities at which human beings are especially inept is monitoring automatic equipment. The man gets worse as the equipment he monitors gets better. When nothing goes wrong and he has nothing to do, he gets restless and bored; his attention wanders; he may even go to sleep. Efficiency requires attention. Attention requires activity"[7]. The ideal arrangement should be for the machines to monitor the man so that if he makes a mistake they will let him know. If human monitoring of mechanical systems cannot be avoided, as it is going to be very likely the case with the progress of automation in industries and elsewhere—it is very much necessary to take into account a larger number of factors which govern human skill in inspection tasks. Mackworth, in his recent address to the Institute of Production Engineers has discussed some of these factors in a very lucid manner. The task of monitoring complicated equipment requires high degree of skill. The operator must be an expert in maintenance of equipment. He must be extremely alert to signals which may indicate a future breakdown in the system. He must be quick in taking effective action or else great damage may be done to the machinery or to the product. The operator's interference may not be needed for long spells of time; yet when the trouble does develop it must be quickly located and eliminated. "The requirement of being so alert", says Mackworth, "that one can snatch up the rare event before it is too late is bound to be a hard proposition for human beings."

Man Versus Machine

The modern trend towards large scale automation in industry and elsewhere forces on us the need for assessment of man against the machine. It has long been known that the human being has certain definite advantages over the machine. The relative merits of man and machine are shown in the table below—

TABLE

Man		*Machine*
Possesses excellent perceptual abilities	..	Possesses speed and power
Recognises patterns easily	..	Can compute much information in short time.
Can improvise in unforeseen situations	..	Reacts faster.
Possesses long term memory	..	Does not tire.
Recognises gross error	..	Carries out complete programme without deviation.
		Handles minor deviations better.
		Possesses short time memory.
		Capable of performing simultaneous operations.

It would be seen from the table above that the human operator is particularly suited to certain types of work and his replacement by a machine in many cases would be uneconomic and at present impossible. Man is good at perception in the sense that he can distinguish things under a variety of conditions. He can adopt his activities to suit the needs of the occasion. He can carry out the same task in more than one way. When an equipment in a system fails, the operator may still avoid complete breakdown by choosing an alternate method. He has a good long term memory which can influence his present action through events which might have occurred long time back. In short, man excels under conditions in which there is a large amount of change and in which he is likely to be confronted with unforeseen circumstances. He brings to any situation a vast amount of generalized information pertinent to that situation. This enables the human operator to choose the proper course of action, even when he has only part of the necessary information. A machine on the other hand, can solve problems only to the extent that the designer anticipates them.

Coming to the disadvantages of the human operator, the most remarkable one appears to be his inability to deal with tasks involving complex coordination of information. It has been mathematically shown that to get maximum reliability from a human operator, the task (ideally) must be designed so that the operator in the man-machine system functions simply as an "amplifier". "In other words, the operator should not be given tasks of coordination which, if analysed mathematically, would require the solution of complex equations. (To the mathematician the time required to learn any physical skill be it learning to walk or learning to fly—is fundamentally the time the body and nervous system require to learn to solve unconsciously a variety of equations). While man is an inordinately clever equation solver, he is not a perfect one. Hence if equations have to be solved in a man machine system it is theoretically desirable (but not always expedient) to turn them over to the machine for solution" [9].

It becomes evident in the light of the foregoing discussion that the place of the human operator in man-machine systems is more or less clarified now. There are some operations for which man is eminently suitable and some which machines perform much better. Operations involving repetitive and stereotyped actions, operations which do not involve any skill, and those operations which need analysis of complex data in short intervals, are most unsuitable for the human being. Automation became a great success in industry because there is very little variability in the operations involved in many industrial processes and machines could easily be devised to do the jobs which hitherto men were doing. But this does not in anyway, decrease the importance of human skill. Human beings are still needed to operate machines economically and to do many other things which no automatic machine has as yet been able to do, nor can be hoped to do in the foreseeable future. Scientific research should, therefore, be directed towards improving the efficiency of the human operator in situations where he is indispensable and most needed. Factors mentioned earlier such as proper design of equipment keeping the human factors in view, creation of congenial working environment and scientific study of human skill are likely to be of great importance in this connection. Study of the characteristics of the human operator in situations where, by his very make-up, he cannot be very efficient or at least as efficient as a machine, is not likely to take us very far in our efforts towards improving man-machine systems.

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