

THEORY OF THE HUMAN OPERATOR IN CONTROL SYSTEMS

II. MAN AS AN ELEMENT IN A CONTROL SYSTEM¹

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I. STATEMENT OF THE PROBLEM

As an element in a control system a man may be regarded as a chain consisting of the following items:

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

(2) A computing system which responds to the misalignment-input by giving a neural response calculated, on the basis of previous experience, to be appropriate to reduce the misalignment; 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 the muscular work produces externally observable effects, such as laying a gun.

Such considerations serve to bridge the gap between the physiological statement of man as an animal giving reflex and learned responses to sensory stimuli, and the engineering statement in terms of the type of mechanism which would be designed to fulfil the same function in a wholly automatic system. The problem is to discover in detail the characteristics of this human chain, such as its sensory resolving-power, its maximum power-output and optimum loads, its frequency-characteristics and time-lags, its amplitude-distortion and whether or not internal cyclic systems enter into it, its flexibility and self-modifying properties, etc., with a view to showing the various advantages and disadvantages of the human operator as compared with an automatic system.

II. HOW THE PROBLEM MAY BE INVESTIGATED

The following are some of the techniques available for studying the human operator as an element in a control system:

(1) We may set him the task of tracking a real target and record his errors by a cine-camera mounted on a gun, and later plot the actual course of the target from knowledge of the motion of the gun and the laying errors at each moment. His performance with different types of control systems can thus be compared, and *ad hoc* results obtained.

¹ The first part of this paper appeared in this *Journal* (1947), xxxviii, 56-61.

(2) We may set him the task of tracking an artificial target following a predetermined course, e.g. by connecting a differential gear between a shaft whose angular rotation is determined by a cam and represents the course, and his control handle; his task is to keep a pointer fixed to the jockey of the differential on a stationary point, and so to balance the target-shaft motion. The movements of this pointer can be recorded on moving paper and will indicate his errors. This method has many advantages of simplicity and cheapness, and makes it possible to repeat exactly the same target-course on successive occasions. Electrical, hydraulic, and pneumatic equivalents of this mechanical system are of course feasible. We can also set 'unnatural' courses containing step-functions, sudden applications of constant velocity to the target, sinusoidal motion, etc., in order to reveal particular characteristics of the operator's performance.

(3) We can attempt to isolate various steps in the chain composing the operator's response. For instance, by suddenly concealing the display we can break into the cycle of operations and momentarily determine the relation between input and output in the 'straight' system—or at least with the system containing only internal feedback such as that provided by kinaesthetic sensations (sensory indications of how far a limb has moved). We can determine the limiting resolving power of the sensory system—e.g. visual acuity—the smallest movements a limb can make, and the maximum power of the limbs with their muscles, by magnifying levers. Physiologists have some techniques, such as recording nerve impulses in sensory and motor nerves and in the brain by means of amplifiers and oscillographs and stimulating motor nerves electrically, which are of great physiological interest, but have as yet, owing to technical difficulties, yielded insufficiently quantitative data to be of great assistance in deriving mathematical laws for the operating characteristics of the human being in a tracking task.

III. THE FIRST TWO STEPS IN THE CHAIN OF RESPONSE

(a) *The sense-organ*

The eye is almost invariably the most suited for tracking tasks, owing to its high sensitivity and resolving power, its two-dimensional and even three-dimensional appreciation of objects. It can detect misalignments as small as 5 sec. of arc (as in vernier scales and coincidence range-finders) and can distinguish between neighbouring lines 1 min. of arc apart, and it has great power of appreciation of form or pattern, e.g. in distinguishing a tank from the surrounding country, or an enemy aircraft from a friendly one. Only in the distinguishing of a constant frequency from a mixed-frequency background—as in detecting Asdic echoes—or in distinguishing a rhythmic modulation from a steady background of mixed frequencies—as in the beating of a submarine's propellers picked up by a hydrophone—is the ear superior to the eye, and therefore is used for tracking some targets in the early stages of the attack. Occasionally the naked eye may be a limiting factor in tracking—e.g. in visual night air-to-air gunnery—but telescopic sights, radar displays of target position, etc., often exceed this limit.

The first problem we meet in analysing the performance of the visual sense-organ is: 'What is the quantitative relation of the angular misalignment between sight and target to the message sent up the optic nerve as "input" which activates the rest of the human operator-system?' Unfortunately, very little is known about this, except that the receptive surface at the back of the eye contains a mosaic of individual receptors which

are individually connected to nerve-fibres, in the region which has the highest resolving power, and that the fineness of this mosaic corresponds roughly with the resolving power of the eye. But how a misalignment between two objects in the retinal image produces something equivalent to the 'error voltage' in a radar set is not known. The problem is further complicated by the fact that the misalignment-image need not fall on the same set of receptors from moment to moment—i.e. tracking can go on in spite of small eye-movements; and of course the particular misalignment to which the operator responds depends on his training and his orders at the time.

Thus, if he is an A.A. gunner he disregards the misalignment between his sights and various enemy tanks or infantry which may be within view, and enemy aircraft apart from that which he is ordered to attack. His training and his orders act as some kind of selector switch in the brain in a way which is completely unknown. It is possible, however, to show that the operator has some quantitative appreciation of the misalignment; he does not act as if he merely had an on-off wiping contact which indicated satisfactory alignment or an unknown degree of misalignment; and he also appreciates the sense or direction of the misalignment. This can be shown by presenting cards with cross-wires and target-dots at various misalignments and asking the operator to state the size of the misalignment when it is compared with a standard misalignment card presented alternately. Ability to do this varies with training and with the time interval between each presented misalignment and the next; but when the cards are presented for 3 sec. each at intervals of about 1 sec., the relation between the physical value of the misalignment and the subjective estimate of it is as in Fig. 1, which gives the mean values for 10 subjects. It is important in such experiments that the cards should all be presented at the same distance from the eye, otherwise a curious conflict occurs between estimation of the angular misalignment and the actual misalignment in units of length on the card. Thus, if we show an unsophisticated person a card pinned to the wall at 15 ft. and ask him to say which of several sizes of cards, which we hold up in turn at a distance of 7 ft., is equal to it, most people will choose some size intermediate between physical equality and angular equality (i.e. half the linear dimensions) with considerable consistency. This type of perception was called 'phenomenal regression' by its discoverer, Thouless (1931), and represents an attempt to compromise between judging physical sizes of objects, which is usually the more important, and their angular size which may more occasionally be required.

Thus we may conclude that under suitable conditions the human operator can appreciate the angular size of a visual misalignment to an accuracy of about 10 %.

The next point is whether the eye is responding continuously to this misalignment. In a task such as reading, where we wish to observe different parts of the field successively, it can be shown by photography that the eye makes jerks, or 'saccadic movements', having a mean duration of 0.03 to 0.05 sec., interspersed with pauses of about 0.3 sec., during which alone the retinal image is sufficiently distinct to be appreciated, under normal circumstances. Thus the eye operates intermittently in a task such as reading. In tracking a target, however, similar photographs show that the eye fixates the aiming-point on the target as steadily as possible, whether the target is stationary or moving, and it can be shown by electrophysiological methods that sensory messages are being sent continuously up the optic nerve. But we shall see later that continuous response by the sense-organ does not imply that the human operator as a whole responds continuously.

It may sometimes be desirable, however, to attempt to smooth rapid variations in misalignment, such as may be set up by fading in a radar receiver, or vibration and bumping in tanks and aircraft; partly in order to reduce the blurring of the misalignment in the retinal image, and partly to eliminate those momentary changes in misalignment which are too rapid for the operator to be able to cope with by useful corrective action. This, as we shall see later, is a much slower process, and elimination of rapid oscillations in misalignment may improve the operator's performance by removing his temptation to try to achieve the impossible.

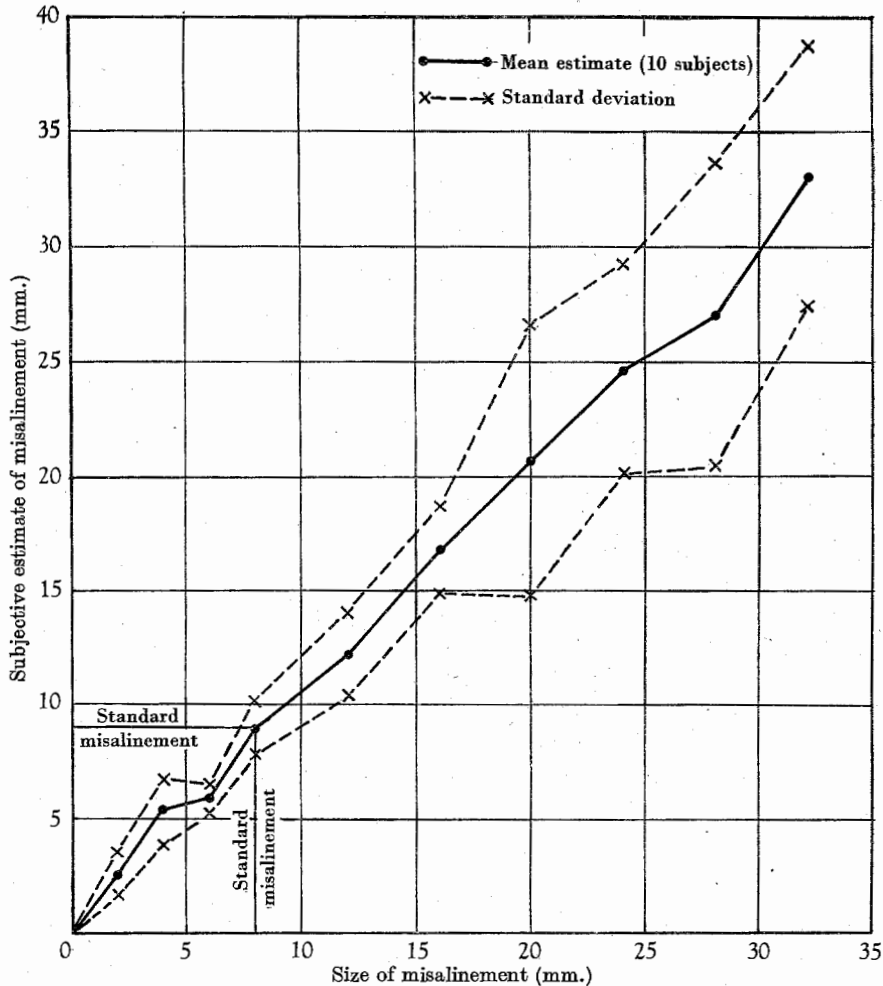


Fig. 1. Relation between the physical value and the subjective estimate of the misalignment.

(b) *The computing system*

In psychological terminology, the operator learns the feel of the controls and finally makes the control-movements which he judges to be appropriate for reducing the misalignment as much as possible. Viewed objectively, this process consists of a modification of the relation between the input, or optic-nerve message, representing the angular misalignment, and the output, or limb-movement. If no instruction is given, it may take

the form of trying and then abandoning various unsuitable methods of moving the controls, for instance with the unsuitable hand, or with an awkward grip, or by action in the wrong direction. There then follows a period of quantitative modification of the ratio of control-movement to the misalignment—i.e. a modification of the 'stiffness' or amplification of the system—and finally there may be an appearance of complicated temporal patterns of control-movements in response to a misalignment, having the object of compensating for the defects of the operator (such as his time-lags) or of the control-gear (such as backlash, striction, and inertia), or overcoming physical limitations such as the time of flight of the projectile (as in aiming off with a shot gun at a flying bird, where no specific rules for aim-off are given). Thus, viewed from the outside, and regarded as a mechanical system such as we should design to operate in the same way, the operator's brain appears as a computing system and amplifier, with variable characteristics and a variable switch-gear between its different input and output elements. For this reason it is not possible to give a single equation which will express the brain's behaviour under all circumstances and at all stages of learning. From the practical point of view the most important points to study are probably (a) the 'natural' or untutored response of the human operator to misalignments; (b) the time taken to modify this so as to reach a steady level of performance on any particular kind of control gear; and (c) the limits and defects of his performance when this steady state has been reached. All these points bear on the design of equipment as well as on the training of the operator.

The first and most marked feature of the cerebral process is its time-lag or 'central delay'. The time-lag between the occurrence of a stimulus such as a flash of light, and the most rapid response the operator can make—such as pressing a morse-key—has been measured by psychologists since the last century; for a single visual stimulus it averages about 0.18 sec., when a warning signal has been given before. When there is no warning, and when the stimulus takes some time to build up, as with a pointer gradually going out of alignment with a mark, and where the operator has a choice of the direction in which to make his corrective movement and also to some extent of its magnitude, so as to try to match this to the misalignment magnitude, it will be slower—about 0.3 sec. Further, in the effort to make a precise and graded response movement he will move the control less rapidly than in pressing a morse-key and the movement itself may take about 0.2 sec., making about 0.5 sec. as the average duration of the whole process. Physiological studies of the response time of the eye and the time taken for impulses to be transmitted up the optic nerve show that these can account for about 0.01 sec. only, and electrical stimulation of motor nerves and records of the start of the limb-movement which results show that this accounts only for another 0.01 sec. approximately. There are left about 0.28 sec. to be accounted for in cerebral processes. Practically nothing is known of these, except that the nerve impulses travel through a number of 'synapses' or junctions between nerve-endings which show a delay of about 0.0007 sec. each. These junctions transmit nerve-impulses in one direction only, from sensory to motor nerves, unlike nerve fibres themselves, which transmit either way. Synapses thus resemble electrical rectifiers; they also store up incoming impulses over periods up to 4 sec. and liberate a stream of outgoing impulses which may outlast the incoming volley by some 5 sec.—the after discharge. Thus they alter the time relations of the incoming impulses. They also show variations in ability to transmit impulses—generally a decrease after repeated stimulation—analogueous to a rise in electrical resistance in a circuit. These changes are often regarded

as the basis for a 'switching' mechanism which would account for learning and modification of behaviour. But all the resistance-changes so far detected are much too short for this, and it is likely that other types of alteration in synaptic resistance are involved in the living animal.

We must therefore ask ourselves whether this delay is more likely to consist of the transmission-time of nerve impulses continuously travelling down an immensely long chain of nerve-fibres and synapses connecting sensory and motor nerves, or of a 'condensed' time-lag occurring in one part of the chain. If the first hypothesis were correct, there would seem to be no reason why a continuous stream of incoming impulses should not evoke a continuous stream of motor ones, just as impulses can follow each other closely in a nerve-fibre or fairly closely even in a synapse. If, on the other hand, the time-lag is caused by the building up of some single 'computing' process which then discharges down the motor nerves, we might expect that new sensory impulses entering the brain while this central computing process was going on would either disturb it or be hindered from disturbing it by some 'switching' system.

These ideas can be tested to some extent by recording the human response to a series of discrete stimuli—such as flashes of light—presented at various time-intervals, to see whether there is a minimum interval within which successive stimuli cannot be responded to. Such an experiment is analogous to physiological investigations of the 'refractory phase' of a nerve or synapse, as pointed out by Telford (1931). The results of Telford and of the writer suggest a refractory period of about 0.5 sec., such that a stimulus presented within this interval after the preceding one is responded to later, or may be missed. If, again, the second stimulus succeeds the first very rapidly—within about 0.05 sec.—it and the first may be apprehended together and responded to as a single one, as if it had registered before the computing system had started to operate. Stimuli coming in between these two time-intervals are either disregarded, responded to after the first, or cause general disturbance and conflict in the operator.¹ The result is to set up a response frequency of about 2 per sec.

It is clear that this limit to response frequency is not determined by the sense-organ as pointed out above, or by the muscle and limb, since a finger can be moved voluntarily as fast as eight times a second, or faster by electrical stimulation; it must apparently be a cerebral limit. Certainly it is possible to make successive movements at a greater pace, as in transmitting morse, typewriting, playing the piano, etc., but in such cases it seems as if either the groups of stimuli composing letters of morse, for instance, must have been learned previously and that these groups then become single 'stimuli' with which the computing system deals as wholes, or, as in the case of reading music, that the page must be open in front of the player so that he can take in a few notes in succession as one group and respond to them as a unit. He could not play a piece at sight so fast if each note were exposed in turn by a moving shutter.

Thus the operator, in tracking, responds intermittently, at a frequency of about 2 per sec. Signs of this are often clearly visible in the records, particularly of untrained operators, and it would appear that when it is less evident, in experienced operators, this can be accounted for in terms of the superposition of a smooth movement, thought to be appropriate to the circumstances, and does not indicate any cessation of their basically

¹ For more detailed experimental evidence see the article by M. A. Vince in this *Journal* (1948), xxxviii, 149.

intermittent response. This conclusion puts the human operator into the class of 'intermittent definite correction servos' apprehending a misalignment, making a single corrective movement, and so proceeding. The next task will be experimentally to analyse the operator's performance, as such, and to see how it is affected by central delay and by distortions or variations in the quantitative relationship between the misalignment at a moment when it is apprehended and the movement which results from it.

REFERENCES

- TELFORD, C. W. (1931). "The refractory phase of voluntary and associated responses." *J. Exper. Psychol.* XIV, 1-36.
- THOULESS, R. H. (1931). "Phenomenal regression to the real object." *Brit. J. Psychol.* XXI, 339-359.

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