CYBERNETICS OF OCULAR MOVEMENT*

BY

D. STANLEY-JONES

Hayle, Cornwall

CYBERNETICS has been defined as "the control of machines by machines instead of by men" (Stanley-Jones, 1957). Its meaning embraces also the pattern of that control. A cardinal notion is the concept of feed-back. This may be simply explained by reference to the most familiar example of cybernetic control, the thermostat of an electric iron.

An electric iron is a machine for converting electricity into heat. It has accordingly, like all machines, an input and an output. The thermostat is the little machine that controls the big machine. It is actuated by the output, that is the temperature of the iron, switching on and off as this falls or rises. It acts on the input. This pattern of cybernetic control, whereby changes in the output (temperature) are made to cause corresponding but inverse changes in the input (current), is known as feed-back, or, more elegantly, as refection.

The refection in the thermostat of an electric iron is so designed that the output or working-temperature may be controlled within pre-set limits. It is a pattern of control the purpose of which is the maintenance of stability. It may therefore be called stabilizing refection ("negative feed-back").

A thermostatic apparatus could be constructed with the wiring reversed, so that, in the terminology of the engineer, the feed-back becomes positive. Suppose the connexions of an electric iron were reversed, so that the current was switched on when the heating-surface passed the upper limit of temperature and switched off as it cooled. Two possibilities arise, depending upon the initial setting.

If the thermostat is switched on, the iron continues to heat up until it has passed the upper safety-limit. The thermostat, its wiring reversed, fails in its stabilizing duties: the current remains on. The iron gets hotter and hotter, and in due course may become red-hot, set fire to the ironing-cloth and then to the whole house, and so end by causing its own destruction.

If the thermostat, on the other hand, is switched off, and the temperature is falling, the iron will lose heat until it falls below its proper working-temperature. The thermostat fails in its task of switching on, and the iron will cool to room-temperature and remain there.

These two sequels of positive feed-back are known as "runaway": runaway to maximum, runaway to zero. Both are due to a reversal of the normal pattern of stability-control or refection. Although the end-results are so

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different, they issue from the same cause, namely reversal of feed-back, operating in two different circumstances.

Certain other cybernetic propositions must be briefly mentioned. An oscillation invariably demands negative refection. This may be illustrated by the pendulum. The input or motive force is gravity; the output is angular displacement. The restoring force is almost directly proportional to the displacement (the criterion of true simple harmonic motion), that is, the input is coupled to the output and by virtue of its direction is patterned on negative or stabilizing feed-back. No positive circuits exist, and the risk of runaway is absent.

An oscillation arising in a previously stable or non-oscillating system may be due to one of two causes. If the oscillation is symmetrical, the fault lies in a delay or time-lag in the cybernetic circuit which (apart from the delay) continues to function more or less normally. If the oscillation is asymmetric, two circuits must be postulated, one for each half of the cycle. An asymmetric oscillation is sometimes due to the total failure of one circuit, and its replacement by another and less efficient means of cybernetic control.

These elementary propositions of cybernetics are the key to the understanding of a great many patterns of control in the physiology of muscles. The obvious mechanical analogy to the muscles and movements of the eyeball is the radar-directed searchlight. The specific properties conferred by radar-direction are that the beam of the searchlight seeks the target and, having found it, follows it. The output must be measured, not as a candle-power, but as the distance-from-goal, or angular displacement between the beam and its target. The input is the power that operates the controlling machinery of the equiposed lantern. The cybernetic structure of this apparatus is designed to keep the error or distance-from-goal to a minimum. Refection is negative, and leads to stability at zero error (which is not the same as runaway to zero).

Ocular Movements

The applications of this illustration to the mechanics of ocular fixation are elementary, and will not be further discussed. Two problems, which have not yet been explained in terms of conventional physiology, have yielded to cybernetic analysis: these relate to coalminers' nystagmus, and to the oculogyric crises of encephalitis lethargica.

Coalminers' Nystagmus.—"The origin of coalminers' nystagmus has never been satisfactorily explained. Some hold that it is primarily psychoneurotic, whereas others suggest that the chief cause is using the eye at levels of illumination below the threshold of perception by the cones, with the result that the fine normal scanning movements of the retina are grossly exaggerated because the macula is in effect blind and the eye has only peripheral vision at these low intensities of light . . . Coalminers' nystagmus may be a type of disuse atrophy of the visual function from lack of light" (Browne, 1951).

This latter view is confirmed by the experimental production of nystagmus in young animals kept in the dark. Chimpanzees reared from birth in darkness developed nystagmus (Riesen, 1950). Puppies similarly reared developed nystagmus in times ranging from 10 to 48 days (Ohm, 1916). Kittens kept in the dark from the age of 4 to 6 weeks developed oscillations of the eye in 4 weeks (three kittens) and 7 weeks (one kitten); they recovered after one week in the light (Browne, 1951).

The first step in the cybernetic analysis of a problem such as nystagmus is to determine the variables (the input and output) which are coupled by feedback. Comparison with the searchlight suggests that the output is the error or distance-from-goal, the input the co-ordinated tonus of the oculomotor muscles. This simple scheme, however, although it will account for a symmetrical oscillation such as Parkinsonian tremor (Stanley-Jones, 1955), fails to explain the asymmetry of the oscillation which is a characteristic feature of many forms of nystagmus. It is necessary to postulate two cybernetic systems acting in opposite directions to account for an asymmetric oscillation.

The problem of nystagmus as an asymmetric oscillation arising in a previously stable system is exemplified in the tabetic gait. The physiology of this condition is familiar, and it is a simple matter to translate it into cybernetic terms.

The feed-back in normal walking arises in the stretch-receptors in the muscle-spindles, and is transmitted to the higher centres by the ascending tracts of the spinal cord. The purpose of these receptors is to signal the degree of muscular stretch, and to inhibit further activity of the anterior-horn cells when the movement has completed its range. If these refractory impulses should be blocked, the motor cells in the cord are bereft of the information necessary for their task, and the muscles overshoot their mark. The upward lift of the foot in the tabetic gait is due therefore to failure of the normal or intrinsic feed-back.

What is it that brings this upward lift to a halt, and throws the movement into reverse? The visual cortex is held to account for the greater part of stability in a tabetic. When the eyes are shut, balance is even more precarious (Romberg's sign) and walking is virtually impossible. This visually directed source of stability is not brought into play in normal circumstances, it takes no part in the unconscious postural reflexes and their intrinsic feed-back. It is therefore an extrinsic feed-back mediated by the visual cortex, which replaces (in tabes) the intrinsic refection of the spinal cord.

The cybernetic structure of the tabetic gait is thus an asymmetric oscillation brought about in a previously stable system by the failure of intrinsic refection, and its replacement by an extrinsic circuit—extrinsic, that is, to the formerly self-sufficing cybernetic controls. It is to be noted that the intrinsic refection mediated by the lower centres (spinal cord) has a low threshold, or high sensitivity to error as distance-from-goal, whereas the refection mediated by the higher centres (visual cortex) has a high threshold or low sensitivity to

error. The system which replaces the physiological feed-back, although deriving from higher centres, is less efficient in the correction of error: hence the stamping gait and wide excursions of the feet in lieu of their even placing in normal walking.

Applying this now to the problem of nystagmus: the output, as before, is error or distance-from-goal, which has to be reduced to zero by negative feed-back. In walking, the goal is the ground; in seeing, the goal is monocular centring (as with the searchlight) or binocular fixation. The intrinsic feed-back has its origin in the cones of the macula, their low threshold and fine spacing being the measure of macular acuity. It is this feed-back from the cones of the central fovea which has failed in miners' nystagmus; and the failure is due to disuse atrophy of the fixation reflexes caused by constant staring at the featureless blank which is the darkly illumined coal-face.

The extrinsic circuit which comes into play when the macular vision fails has its origin in the rods of the retinal periphery, the low response of which to matters of detail renders them ill fitted to serve the purpose of fixation. Their proper role in the physiology of vision derives from their high sensitivity to faint light—which is the craft-secret of the night-watchman and the lookout man, who use peripheral rather than central vision to spot blurred objects or slight movements in the dark. The nystagmic miner brings his eyes back from their rolling excursions under the control of peripheral vision, which comes into play only when the distance-from-goal is large.

The two unequal halves of the oscillations of nystagmus are explained, as in tabes, by two separate cybernetic systems. The slow outward swing and the upward lurch of the feet are due to the failure of the intrinsic feed-back with its high sensitivity to error. The correcting jerk of the eyes and the stamping of the feet are brought about by an extrinsic and unwonted feed-back which comes into action only when the error is pathologically large.

The asymmetric oscillations of nystagmus and tabes may be briefly contrasted with the symmetrical oscillations of tremor, shivering, and trembling. These three varieties of muscular oscillation can be explained, not by the failure of one circuit and its replacement by another, but by a delay or time-lag introduced into the otherwise unimpaired cybernetic controls. The muscle overshoots its mark because the signal to stop arrives a fraction of a second too late. This overshooting of the mark is registered as error or distance-from-goal, and negative refection, with its sensitivity undiminished, now comes into play in the opposite direction (but still negative in sign): again an overshooting of the mark occurs and the cycle of the tremor completes its return phase—symmetrical with the first because the same circuit, with the same delay, is operative (Stanley-Jones, 1955).

Symmetrical oscillations, in short, are due to a delay, and asymmetric oscillations to a failure, of negative refection.

The cybernetic principle which explains an oscillation as a failure of negative or stabilizing feed-back is also exemplified in the movements of the

pupil. Closure of the pupil in response to a bright light is usually a smooth change from one position to another, with little or no oscillation. The reflex that brings this about arises in the retina, and the threshold is much lower in the central cones than in the peripheral rods (De Launay, 1949). If the beam of a slit-lamp is directed to the outer regions of the retina which have a low sensitivity for the pupillo-motor reflex, the pupil responds by a long series of oscillations, up to two hundred or more (Campbell and Whiteside, 1950). The normal feed-back mediated by the low threshold cones has been replaced by an abnormal feed-back mediated by the high threshold rods, and the oscillation indicates a breakdown of stability.

Parkinsonism.—In certain circumstances, sometimes naturally and at other times only in disease, muscles can exhibit a runaway. This must necessarily be due to positive or self-exciting refection somewhere in the neural circuit. The oculogyric crises of post-encephalitic Parkinsonism can be explained on these lines.

In an oculogyric crisis there is an attack of eye-rolling, usually upwards, or upwards and inwards, lasting anything from a few minutes to several hours. The patient is completely incapacitated, being virtually blinded by the extreme upward retreat of the eyes under cover of their lids, leaving only the whites still visible, and is unable to bring the eyes down to their proper position. These crises occur in no other disease, nor in any variety of Parkinsonism other than that associated with lesions of the substantia nigra.

The upward and inward direction of the spasm is noteworthy. It represents the total resultant of spasm of the muscles controlled by the third nerve, lacking the downward component of the fourth and the outward component of the sixth. Rarely, all three nerves are involved, and when thus balanced the eyes lock centrally in a fixed stare (Walters, 1954).

Certain familiar details of anatomy are relevant here. Of the two principal forms of paralysis agitans (Parkinson's original disease, and that due to encephalitis lethargica), only the latter presents these oculogyric crises. The post-encephalitic variety is due to disease of the substantia nigra, which is often untouched in true Parkinsonism (Stanley-Jones, 1956b). The substantia nigra is penetrated by the fibres of the third cranial nerve, but not by the fourth and sixth nerves.

The oculomotor muscles are lavishly supplied with stretch-receptors and muscle-spindles. In spite of many assertions to the contrary, "neuromuscular spindles are obvious and constant features of all the human extra-ocular muscles" (Merrillees, Sunderland, and Hayhow, 1950). There is one sensory spindle to about every five muscle-fibres, for in no set of muscles is there greater need for extreme precision and delicacy of control. The refection supply is proportional to the required accuracy of movement: the levator of the eyelid has the smallest supply (Merrillees and others, 1950), and

the inferior rectus used for reading and in close handwork has the richest (Cooper and Daniel, 1949).

In oculogyric crises the eyes move always conjugately, never erratically or independently. It is certain therefore that disease of the substantia nigra does not irritate the *outgoing* motor fibres, as this would cause irregular movements of one eye only. If it affects the nerves at all, it must act by setting up a temporary irritation of the sensory fibres coming in from the stretch-receptors, thereby throwing out of gear the goal-seeking mechanisms needed for binocular vision.

The usual result of the disturbance of cybernesis is a runaway to maximal and un-coordinated effort on the part of all the muscles supplied by the third nerve, a generalized spasm leading to the extreme and sustained upturning which is the typical crisis. Less frequently, oscillations are set up, known as myoclonic spasm, wherein the eyes move rhythmically in one direction or the other (Duke-Elder, 1949). In a series of 59 cases in which the direction of spasm was observed, there were 44 patients whose eyes turned up, two only whose eyes moved to the side, and thirteen whose eyes moved up and/or down (Hall, 1931). Nystagmus-like movements of the eyes are commonly observed during the crises.

The cybernetic explanation of the ocular symptoms in encephalitis lethargica is supported by the presence of other forms of oscillation. Oscillation, it will be recalled, invariably demands negative feed-back. The true oculogyric crisis occurs only in about 20 per cent. of patients (Hall, 1931), and myoclonic spasm is much less frequent. A third anomaly, blepharoclonus, occurred in 96 per cent. of one series and in 92 per cent. of another. "On closing the eyelids, the lids are thrown into a series of rapid clonic movements, of fairly large amplitude. These clonic movements are regular in their rate and amplitude, and persist so long as voluntary closure of the eyelids is maintained. When the eyelids are closed in sleep, no movements are seen" (Cooper, Daniel, and Whitteridge, 1955). This last observation tallies with the belief that tremor in general is due to a defect of the anti-gravity augmentor system, which relaxes its tonus during sleep (Stanley-Jones, 1956a). It is presumably a cybernetic failure of the refractory fibres of the third nerve, arising in the muscle-spindles of the augmentor system and traversing the diseased tissue of the substantia nigra, that is responsible for these characteristic features of post-encephalitic Parkinsonism.

Psychomotor Symptoms.—One of the most baffling features of the oculogyric crises, as also of nystagmus, is the relation of these purely physical and muscular spasms to outbursts of emotion. They are often precipitated by, or appear simultaneously with, attacks of acute fear or anxiety, or paroxysms of screaming and crying. During the attack, the patient may be acutely depressed, perform repetitive obsessional movements, or be occupied by obsessional thoughts. He may also have ideas of persecution which are

characteristic of paranoia, the form of insanity due to deeply unconscious hate. These emotions of fear, anxiety, and hate, together with the accompanying screaming, are of orthosympathetic origin and therefore carry in them the pattern of positive or runaway refection (Stanley-Jones, 1957).

Emotional outbursts are also a feature of coalminers' nystagmus. The psychic aspects of the two diseases have much in common. The same precipitation into an uncontrolled runaway may coincide with or follow the onset of an attack. This may sometimes be brought about to order, by asking the miner to hold his head askew in just that position which brings on his symptoms, and which is usually the position he has to hold while working at the coal-face. "We stand the man up in front of a window, place our hands behind his head and ask him to look up. Soon he begins to tremble, first in his neck muscles, and then perhaps in his arms, and even all over his body. The neck muscles become rigid, and the eyes converge strongly. He struggles to get away, and complains that he cannot bear it any longer" (Butler, 1939).

Discussion

Nystagmus and the oculogyric crisis have therefore six features in common: nystagmus itself, spasm of the oculomotor muscles, fluttering of the eyelids, tremor, rigidity, and psychic symptoms of acute anxiety. Yet no two diseases could be more unlike in their aetiology. Oculogyric crises occur only in Parkinsonism that follows a virus-infection of the brain. Nystagmus occurs chiefly as an occupational disease in an otherwise healthy miner. The clinical manifestations of the two symptoms are totally unlike, and there is no possibility of confusing one with the other. Only their cybernetic structure is similar: six symptoms in common which, combined in differing patterns, constitute two entirely separate diseases.

Such a coincidence of symptoms in no less than six points in two diseases of radically different origins, as far as external causes are concerned, must surely point to an underlying pathology in common. In the case of the oculogyric crises, there is an interference with ocular refection by toxic or secondary damage to the third nerve as it traverses the substantia nigra. With nystagmus, ocular refection is upset by the replacement of a normal by an abnormal feed-back, namely macular by peripheral vision.

The system of refractory control is more highly organized in the oculomotor muscles than anywhere else in the body. It is therefore at this site that it is most likely to break down from trivial defect. For this reason no microscopic evidence is yet available to support the cybernetic theory of ocular disease. Moreover, the two diseases, not being fatal, rarely come to autopsy.

The anatomical route of spread of this runaway refection may at least be conjectured. The lowest co-ordinating centre for the incoming messages from the muscle-spindles, in which the refection is disturbed, must lie in or near the oculomotor nuclei in the midbrain. Ascending pathways convey to

the cortex proprioceptive information about the resulting position of the eyes.

Three areas of frontal and pre-frontal cortex may be concerned, namely Areas 6, 8, 9-plus-10. Area 6 gives rise on stimulation to slow writhing movements resembling torsion-spasm. Area 8 is the headquarters of the voluntary ocular movements. Areas 9 and 10 are suspected of being implicated in the completely purposeful movements of obsessional neurosis and mania (Le Beau, 1951). If the sensory information of muscle-position from the oculomotor muscles ultimately reaches Area 8, a spreading of the disturbance backwards will involve Area 6 and bring on the torsion-spasms; a spreading forward will encroach on Areas 9 and 10 and set in being the compulsive patterns of thought and action.

The site of the cell-bodies of the afferent fibres which mediate this refection from the oculomotor muscles is still undetermined. The oculomotor nerves differ from the typical series of spinal nerves in having only motor roots. There is no separate posterior, sensory root, and nothing corresponding to the posterior-root ganglion. This anomaly has caused an endless amount of speculation, both in searching for the missing sensory fibres and in explaining away their presumed absence.

It is now known for certain, on purely theoretical grounds, that these fibres must exist. Distally, the muscles themselves have a rich supply of muscle-spindles and other types of sensory organ to set in motion the refractory impulses so essential for binocular vision. Ascending electrical impulses brought about by stretching the muscles have been recorded in the oculomotor nerve. There is no trace at the upper end of the nerve, however, of the fibres which convey ascending refection, nor is there any suggestion of a sensory nucleus.

The import of these morphological difficulties lies in its relation to the proposed explanation of the oculogyric crises in terms of cybernetics. These attacks occur only in disease of the substantia nigra. They can be caused only by damage to the incoming refractory nerves or blockage of their ascending impulses, as they traverse this diseased part of the midbrain. It is essential therefore, if this theory is to be accepted, that the physical whereabouts of these missing fibres should be established: it must be proved that they do in fact pass with the outgoing motor fibres through the substantia nigra.

Recent work has thrown doubt on this very point. Dr. Sybil Cooper and her colleagues have established that the refractory impulses leave the main trunk of the third nerve and continue their upward journey into the brain along the trunk of the fifth nerve. Their further course within the substance of the brain is not easy to follow. In two regions only could they be detected with certainty: both regions were among the fibres or nerve-cells of the fifth nerve (Cooper, Daniel, and Whitteridge, 1955). As this nerve lies nowhere near the substantia nigra, it is difficult to explain how disease of the latter nucleus can account for the oculogyric crises.

The threatened impasse may be circumvented by a study of the fibre-population of a typical motor nerve. Only about 50 per cent. of the fibres in the spinal motor nerves are actual motor fibres carrying descending impulses from the anterior-horn cells to the muscles. The remainder are concerned with proprioceptive feed-back, travelling in both directions to complete a refractory circuit.

The muscles around the eye have a greater need of absolute accuracy in their control than any other group, and they have a richer supply of spindles; their nerves, presumably, would carry a larger ratio of sensory to motor fibres than any other motor nerves in the body. The sixth cranial nerve which supplies the lateral rectus is as large (in the foetus) as the nerve which supplies the gluteus maximus. The ratio of muscle-volumes, however, is 1 to 74, the coarse muscle needing only this fraction of the delicate control needed by the muscles of the eye (Stibbe, 1929). Relative to the size of its muscle, the sixth nerve is the largest in the human body (Whitnall, 1932).

The route taken by some, at least, of these ascending fibres in escaping from the main trunk of the oculomotor nerve has been ascertained. There are some minute branches passing between the third and fifth nerve in their passage through the cavernous sinus (Whitnall, 1932). These branches are so small that many standard text-books on anatomy ignore them, or give them only a brief notice in small print. It has been established, however, that these small neural offshoots from the oculomotor nerves do in fact convey the necessary feed-back (Whitteridge, 1955). The cell-stations of these nerves would be in one or other of the nuclei of the fifth nerve, presumably in that of its mesencephalic root. If this hypothesis is correct (and it seems well founded), the pathway of proprioceptive refection does not traverse the substantia nigra.

There are quantitative considerations, however, which cannot be ignored. These variant branchlets of the oculomotor nerve are small, indeed minute, compared with the main trunk: there is no question of the nerve splitting, in a more or less equal dichotomy, as it ascends toward the brain. Now the probability is great that at least half of the bulk of the oculomotor nerve is concerned with refection. The minute branchlets leaving it to join the fifth nerve can account for only a fraction of that half. A considerable residue of proprioceptive fibres must therefore be left in the trunk of the third nerve, and will travel with it through the substantia nigra. It is this residue of ascending cybernetic fibres which, it is believed, is secondarily affected by encephalitis lethargica, with the production of the oculo-lyric crises.

Summary

Cybernetics is the pattern of control of machines by machines, instead of by men. Certain cardinal notions are stated relating to negative and positive refection (feed-back). Oscillation demands negative refection with a defect or time-lag. If the oscillation is symmetrical, there is a defect in one

cybernetic circuit; if asymmetrical, two circuits are involved, one for each phase of the cycle. Runaway, whether to infinity or zero, is necessarily due to positive refection. These propositions are exemplified in the thermostat, the pendulum, and the radar-directed searchlight.

Coalminers' nystagmus is an asymmetric oscillation caused by the replacement of the normal intrinsic refection from the low-threshold retinal cones with their high sensitivity to error, by an abnormal extrinsic refection from high-threshold peripheral rods.

The tabetic gait has cybernetically an identical structure: the normal intrinsic refection from the low-threshold muscle-spindles is replaced by an abnormal extrinsic refection from the sense of vision (as in Romberg's test).

Pupillary oscillations may be obtained by throwing the beam of a slit-lamp onto the retinal periphery, which excites an abnormal cybernetic circuit with high threshold (or time-lag) for the pupillo-motor reflex.

Oculogyric crises are due to muscle-spasm or runaway to maximum. There is an interference with the cybernetic or proprioceptive impulses from the oculomotor muscles.

Six points of similarity between nystagmus and oculogyration indicate a common pathology, namely disorganization of ocular feed-back.

Emotional symptoms in both diseases may be explained in terms of cortical anatomy.

The anatomical pathways of cybernetic impulses from the oculomotor muscles are discussed. A small fraction of the ascending fibres is known to leave the third nerve and to join the fifth. The larger residue travels in the third nerve through the substantia nigra. The damage to this nucleus in post-encephalitis is the cause of the oculogyric crises.

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