NATIONAL PHYSICAL LABORATORY

SYMPOSIUM No. 10

Mechanisation of Thought Processes

VOLUME II

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SESSION 4A

IMPLICATIONS FOR BIOLOGY

Chairman: PROF. J. Z. YOUNG, University College, London

Chairman: SIR FREDERICK BARTLETT, Applied Psychology Research Unit, Cambridge

SESSION 4A

PAPER 1

SENSORY MECHANISMS, THE REDUCTION OF REDUNDANCY, AND INTELLIGENCE

by

DR. H. B. BARLOW

BIOGRAPHICAL NOTE

HORACE BARLOW, Physiological Laboratory and King's College, Cambridge. Age 36. Studied Physiology at Cambridge and Medicine at Harvard and London (Univ. College Hosp.). Has worked on various aspects of vision, including eye-movements; spatial properties of receptive fields in the frog's retina; changes in temporal and spatial summation with level of adaptation; and thresholds as signal/noise discriminations. Worked for a year with S. W. Kuffler at Johns Hopkins on changes in retinal organisation in the cat's retina during dark adaptation. Interested mainly in the nervous organization of the visual pathways.

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SUMMARY

PSYCHO-PHYSICAL and physiological investigations have shown that the eye and the ear are remarkably efficient instruments: consequently the amount of information being fed into the central nervous system must be enormous. After a delay, which may vary from about 100 msec. to about 100 years, this information plays a part in determining the actions of an individual: therefore some of the incoming information is stored for long periods.

The argument is put forward that the storage and utilization of this enormous sensory inflow would be made easier if the redundancy of the incoming messages was reduced. Some physiological mechanisms which would start to do this are already known, but these appear to have arisen by evolutionary adaptation of the organism to types of redundancy which are always present in the environment of the species. Much of the sensory input is not shared by all individuals of a species (eg. stimuli provided by parents, language, and geographical locality) so a device for "learning" to reduce redundancy is required. Psychological experiments give indications of such mechanisms operating at low levels in sensory pathways, and "intelligence" may involve the capacity to do the same at high levels.

In order to exemplify the operations contemplated, a device which reduces the correlated activity of a pair of binary channels is described.

THE usual mechanistic approach to the higher nervous system begins with a consideration of the factors which can be shown to have an immediate effect on the output of the nervous system. The commonest starting point is the simple monosynaptic reflex in which a single sensory input controls a single motor output, as shown diagrammatically in *fig. 1(a)*. The next stage is to elaborate this by taking into account other sensory modalities, inhibition, internuncial neurones, and controlling neurones from elsewhere

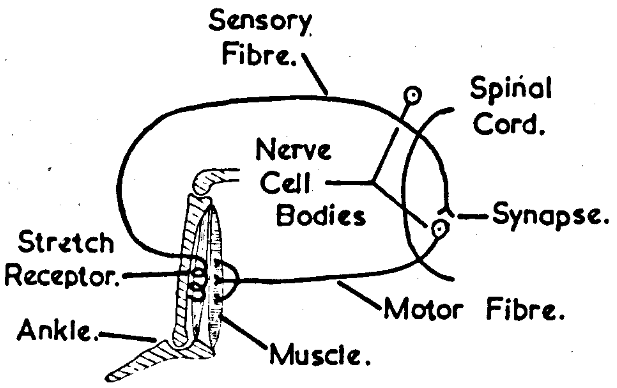

Fig. 1(a)

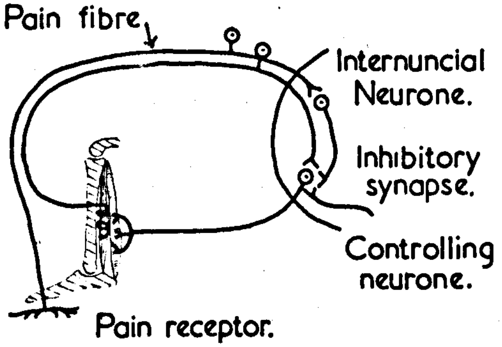

Fig. 1(b)

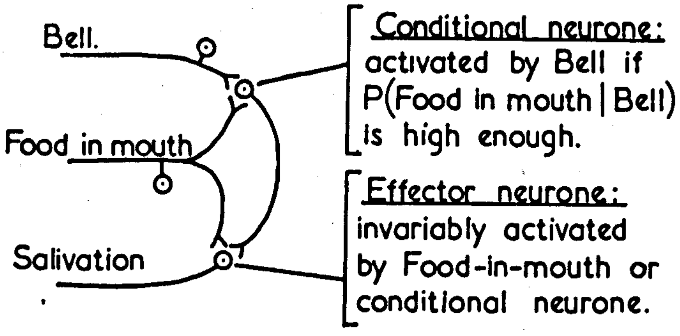

Fig. 1(c)

Fig. 1. Diagram showing approach to higher nervous function from motor (effector) side. (a) monosynaptic stretch reflex; (b) same with addition of internuncial neurones, controlling neurones from other parts of the central nervous system, and inhibition by pain endings; (c) conditioned reflex.

in the nervous system, as shown in *fig. 1(b)*. With all its trimmings this gets one to a stage of complexity perhaps comparable to that of an automatic tracking radar set, or the automatic pilot of an aeroplane. It will show none of the plasticity or adaptability to new surroundings which is characteristic of the higher nervous system, so the Pavlovian conditioned reflex is next introduced. The principle here is that if there are two sensory stimuli (Bell and food in mouth), one of which (food in mouth) always produces a response (salivation), then if they occur jointly with sufficient frequency, the one which, to begin with, did not cause a response, begins to do so (Bell alone causes salivation). This is shown diagrammatically in *fig. 1(c)*, and is perhaps the simplest type of learning behaviour that has been studied in animals, though it has not been investigated in a simple isolated preparation as the diagram might suggest. Uttley (1954, *refs. 22 and 23*) has clarified the principles of operation of such mechanisms and built conditional probability devices which show the same properties of learning and inference.

Now the simple feedback diagram in *fig. 1(a)* has a single input channel, *fig. 1(b)* and *(c)* have two inputs, and Uttley's machine has up to five inputs; but a human brain has something like 3×10^6 sensory nerve fibres leading into it. If it could be supposed that a million or so devices like that of *fig. 1(c)* would deal with the sensory inflow one would be well satisfied with the understanding gained from this approach: but this is not so. The essential operation in a conditional probability device is to measure the frequency of occurrence of *combinations* of activity in the input. Now if the number of binary inputs is increased from two to a million the number of possible combinations is increased from 2^2 to $2^{(\text{million})}$; an arrangement like that of *fig. 1(c)* takes one less far than at first sight appears. I think it follows from this consideration that conditional probability machines cannot be fed with raw sensory information, and the problem of digesting or processing the sensory information entering the brain is an important one. Furthermore, modern electrophysiological techniques are making it possible to record from nerve cells at various levels in the sensory pathways, so this is a problem which is becoming accessible to experimental investigation.

In this paper I have first tried to make rough estimates of the rate at which information flows into the human brain. It is then suggested that an essential step in organising this vast inflow is to derive signals of high relative entropy from the highly redundant sensory messages. For this something similar to the optimal codes discussed by Shannon (1949, *ref. 19*) needs to be devised for the sensory input, and the steps required to do this are considered. Finally, a modified form of such recoding is proposed, some evidence that it occurs is brought forward, and it is suggested that the idea may be extended to cover some of the processes going on in consciousness and called reasoning or intelligence.

1. THE SENSORY INFLOW

(a) Properties of Nerve Fibres

We are equipped with sensory instruments of astonishing sensitivity and versatility which supply information about the environment to the central nervous system. This information is carried along nerve fibres, and since a good deal is known about what these fibres can and cannot do, one can derive an approximate upper limit to the rate at which information enters the brain. If the simple assumptions are made that (i) the maximum frequency of impulses is 700/sec, and (ii) in 1/700th. sec a nerve can only be used to indicate the presence or absence of an impulse, then the maximum rate at which it can transmit information is 700 bits/sec. Mackay and McCulloch (1952, *ref. 16)* point out that the nerve might be used more efficiently if, instead of detecting the presence or absence of an impulse, the intervals between impulses are used to convey information. Using such pulse interval modulation, and assuming (i) accuracy of estimation of intervals of 0.05 msec, (ii) a minimum interval of 1 msec, they give the maximum capacity as 2880 bits/sec. This would require a mean frequency of 670 impulses/sec, but at a mean frequency of 50/sec, such pulse interval modulation still allows 500 bits/sec to be transmitted. These figures are actually too low, because Mackay and McCulloch incorrectly assumed that the optimum distribution of intervals was uniform instead of exponential: however, if the other assumptions are granted, they show clearly that a single nerve fibre could be used to transmit information at a rate well above 1000 bits/sec.

The total capacity of the sensory inflow appears to be above 3×10^9 bits/sec, but it is certain that nothing like the full capacity is utilised. The mean frequency of impulses must be far below the optimum; peripheral nerves appear to use pulse frequency rather than pulse interval modulation, so that there will be high serial correlations between the values of intervals; furthermore, there are generally considerable overlaps in the pick-up areas of neighbouring fibres, which are therefore bound to show correlated activity. Finally, the figure for the performance of a nerve fibre given above might be approximately true for the large diameter fibres, but those of smaller diameter, which make up a large fraction of the total number, must have a smaller capacity. It would be pure guesswork to try to allow for these factors, but one can get indications of the utilised capacity from two other sources.

(b) Sensory Ability

Jacobson (1950, 1951 *refs. 13,14)* has made estimates of the informational capacity of the ear and the eye. For the ear he calculated 50,000 bits/sec from the number of discriminable pitches (about 1450), the number of discriminable intensities at each pitch (average about 230), and the time required