Papers and Originals

What Can We Know about Memory? *

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On 27 March 1885 the young surgeon Victor Horsley gave a Friday evening discourse at the Royal Institution under the title "The motor centres of the brain and the mechanism of the will" (Horsley, 1885). He was standing in for a "distinguished man who has been prevented by a most painful bereavement from addressing you tonight." I have not been able to find out who this man was, but his bereavement was our gain, since the young Horsley was induced to show us something of his thinking about brain and mind. The bulk of the lecture was essentially an account of the parts of the brain and their involvement in reflex action, and they show us a picture astonishingly similar to what might be given in a lecture today. True we don't talk about the flow of nerve energy from sense organs through the brain to muscles. But basically our schemes of thought have developed shockingly little in the years since Hughlings Jackson, Ferrier, and Horsley did their work. I shall try to discuss some of the difficulties that have prevented the development of a better model and perhaps can also point to ways in which they are beginning to be overcome.

The Surgeon and Psychology

Horsley began his lecture by saying "It might be asked 'What has a surgeon to do with psychology?'" To which, he says, "I would answer 'Everything.'" And among his reasons, "Surgeons, rather than physicians, see the experiments which so-called Nature is always providing for us—experiments which, though horribly clumsy, do on rare occasions . . . lend us powerful aid in attempting to solve the most obscure problems ever presented to the scientist." Luckily I shall not be expected to evaluate the accuracy of his claim for the surgeon against the neurologist. I take it that it was in character for him.

The purpose of reciting all this, however, besides allowing something of Victor Horsley to appear ghost-like before you, is to explain why the question mark in our title is essential in the present state of knowledge of the nervous system. Perhaps we have not given enough thought to what it is that we expect to find from our studies. Horsley claims that the surgeon has "everything" to do with psychology. This is a takeover bid indeed. Few would make it so outspokenly even today. And yet slowly but relentlessly this is the way things are going. Of course it is not surgeons only; I have used the quotation as a concession to piety on this occasion. But knowledge about the brain, acquired by scientists, surgeons, physicians, and psy-

chologists, is increasingly taking a leading place in the framework of the system of communication by which all of us direct our lives. Of course knowledge of the nervous system has played a central part in philosophy for a long time. I need only remind you of Descartes, Bishop Berkeley, and Immanuel Kant.

Knowledge and the Brain

We know a vast amount about the variables of memorizing in ourselves from the thorough investigations by psychologists. Yet we have hardly any firm information about the changes that go on in the brain during learning (John, 1967). The first question is, What sort of facts about the brain, if any, would be useful information about memory? This is not nearly so clear as many who talk glibly about changes in synapses seem to assume. Even if we understood the nature of synaptic changes in learning, we should still not necessarily know how it is that many neurons co-operate to produce a representation useful to the animal or man. Many psychologists not unreasonably conclude that it is not worth trying and that the brain had better be treated as a black box.

Further, there are profound ambiguities in any takeover programme of psychology by neurologists. It is a truism that all speech, and hence all knowledge, is in some sense a product of the brain. It might seem obvious, therefore, that study of the brain is the most fundamental of all studies. But we are then brought up short by the question, "With what methods shall it be studied?" For, historically, study of the brain has come last rather than first among the sciences. We can only pursue it with the techniques of language, mathematics, and science that we have inherited from other studies, which themselves are products of the activities of brains. Of course we can improve these techniques, and find entirely new ways of using the brain. But can new methods resolve the circularity in the question "How shall we study that which studies?" We cannot answer this at present, but human brains are very powerful devices, and I believe that over the next decades and centuries they will evolve new semantic and other techniques that will make our present concerns seem as simple-minded as Descartes's model for the seat of the soul.

How Knowledge is Acquired

Some glimpse of the possibilities may emerge if we attack the hardest part of the questions that arise from our title. What is it to "know" about memory or indeed about any other matter? There are many definitions of "knowledge" in dictionaries, encyclopaedias, and philosophical treatises. I prefer to try to extract one from the works of someone who has

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studied the question of how knowledge is acquired—for this, like everything else, can be treated as an empirical question. I refer to the child psychologist Jean Piaget. He says, "... no cognition (*connaissance*), even perceptual, is simply a copy of the real, because it always includes (*comporte*) a process of *assimilation* to anterior structures" (Piaget, 1967). These structures are what Piaget calls the "schemas," defined as "cognitive structures each of which has reference to a class of similar action sequences" (Flavell, 1963). This is therefore an attempt to isolate elements of human behaviour. What especially concerns us is that for each schema there is presumably a corresponding level of cerebral organization. Thus at one level the sucking sequence of a baby is a schema, and so at the other is, say, the method of long division as learned by a 10-year-old or the logical strategy by which a civil engineer designs a bridge.

Particularly important is the remark that cognition includes *assimilation* to pre-existing schemes. This means that the ways of acting that we have must serve as filters, organizing the input of the individual along lines that have been found useful for homeostasis. To quote Piaget again, "... all cognition is tied (*liée*) to an action and to know (*connaître*) an object or an event is to utilize them by assimilating them to action schemas... knowledge (*les connaissances*) does not constitute a copy of the surroundings but a system of real interactions, which reflect the self-regulatory system of life rather than things themselves (Piaget, 1967).

The studies of Piaget not only make us think what we mean by knowledge but also give valuable suggestions of how human behaviour may usefully be itemized and thus of how we may find out how the brain does it. We need first to specify what sorts of items are stored. The suggestion is that the various items are often related to each other and that the store grows gradually, in some sense as a unified structure. New items are assimilated to the old. I want to suggest that this coherence between items may well be the secret of the method by which they are addressed and retrieved. Can we find any clues in brain physiology on how this may be done?

Value of Memory

The actions that the nervous system produces are of course organized by heredity so as to be appropriate to the life of the species. In this sense the nervous system can be said to *represent* the environment in which the species lives. The value of a memory is that it improves the fit between this representation in the brain and the *particular* environment that the individual experiences. We shall see at once that the memory systems of animals are likely to be *species-specific*. The animal will learn what it is useful for it to learn—that and only that. Of course there may be underlying principles that are common to all. But it is clear that the capacity to change in this way is likely to be a *highly specialized function of the brain*. It may be based on some general property of neurons, but yet be effective only through the presence of very special mechanisms, produced under the control of the D.N.A., and selected to make records of just those features that are relevant for that species. In fact all animals that learn well have such special equipment, associated with nerve centres containing a large number of small cells. We find these regions of small cells in some of the more active errant polychaete worms (*Nereis*), in cephalopod molluscs, in insects, especially the social ones, in arachnids, and in vertebrates. Of course, we know shockingly little of the varied properties of these systems (among many strange anomalies is the presence of very large centres of this sort in the clumsy king crab). Conversely we notice that simpler animals and parts of the nervous system that perform executive function, notably the spinal cord, do not have these capacities for learning and do not have

large numbers of small cells (though they all have some of them—see below).

Phenomena basic to learning may be present in all nervous systems (indeed in all cells), and we learn much from the changes in responsiveness of reflex systems such as the post-tetanic potentiation in the spinal cord or the learning of insect ventral nerve cords. Similarly we learn a great deal from the adaptive changes in the firing of single large nerve cells such as those of the sea-hare *Aplysia*. But I believe that in order to learn about the phenomena that we usually call memory we must study the operations of the *special* equipments that serve for recording in the nervous system.

In the octopus and its relatives we have an opportunity to see how special learning machinery has been developed for a particular way of life. This animal finds its food partly by visual and partly by tactile exploration, and it has anatomically definable memory systems for each of these senses (Fig. 1). The related squids and cuttlefishes find their prey by sight and use the arms only to seize it. They have no special equipment for a touch memory.

FIG. 1.—Diagram of touch and visual learning centres and their connections in *Octopus*. (Modified from Young, 1966.)

Actions Effective for Survival

We must now go on to ask how is it ensured that with the information of its given receptors an animal learns to take actions that are more effective for survival? The essential feature must be that the animal can make one of two or more distinct responses to the activation of any given classifying system. It is in the presence of these alternative possibilities that memory systems differ from the more fully determinate reflex ones. In higher animals the primary classifying systems presumably cannot be the seat of the changes that create the store. The cells of the primate striate or auditory cortex, or primary somato-sensory area, like those in the eyes or ears themselves, have to report the occurrence of various configurations of stimuli that are parts of *many* situations that can be remembered. There must be further reclassifying cells in a hierarchy proceeding away from the sensory and towards the motor areas. Somewhere along the line there are the systems of cells with alternative possible outputs, which are changed by the process of learning.

It may be interesting to consider the situation in *Octopus*. Here it is possible that the hierarchy of classifying cells is

much simpler and can perhaps even be treated only as a single layer (Fig. 2). It may be that in this simple system the cells that detect contours of different orientation, or objects of different roughness, are themselves able to influence the alternative pathways that make an animal attack or retreat.

FIG. 2.—(a) A hypothetical non-learning octopus ancestor. Touch reflexly produces drawing-in and pain produces rejection. Collaterals activate amacrine cells to produce a temporary inhibition of the antagonistic reflex. (b) Diagram of the pathways probably involved in learning of a touch discrimination in an octopus after removal of the higher nerve centres. A classifying cell (*class.*) detects the occurrence of a particular degree of roughness by the suckers (*touch*). Initially this cell has outputs that can activate either the motor neurons to draw in (*mot.*) or those to push away the object touched. Which of these it activates depends on the signals of taste or pain that follow. These signals, besides exciting the appropriate motor neurons (*mot.*), also, through collaterals, activate the small amacrine cells (*am.*), initiating the production of an inhibitor which blocks the unwanted pathway. Thereafter stimulation of the cell (*class.*) always yields whichever response has been learned.

In order for effective forecasts to be made there must be systems that indicate whether the results of the actions that were performed were good or bad for the animal. This is, of course, the function of the various internal receptors for the detection of the satisfaction of hunger or the avoidance of trauma or pain. These signals of the results of action (or reinforcers) are fundamental features of memory systems—a fact much obscured in ourselves because we do not need such carrots for every act of learning (see Tapp, 1969, for studies of reinforcement).

In order for the signals of results to be effective they have to be brought together with some record of the sensory events of the recent past. This is one function of the short-term memory systems, which have been studied in various species. In *Octopus* there are separate sets of circuits that have this function for the visual and touch systems. If these lobes are removed the signals of food reward and of pain are not correctly delivered. The animals then have particular difficulty in learning not to attack in situations involving trauma.

There is much to suggest that the circuits in the base of the mammalian forebrain, such as those through the hypothalamus and hippocampus, have similar functions, bringing signals from the various detectors, such as taste and pain, to the cortex. This is the obvious interpretation for the presence of reward centres whose self-stimulation is either sought for or avoided by an animal (Olds and Milner, 1954). It agrees with much of the evidence that extirpation or stimulation of the hippocampus "stops the arrival of these signals telling of the

effects of the action" (Luria, 1966). This is also consistent with the memory defects reported after lesions in the hippocampus or elsewhere in the Papez "circuit of emotion."

In the touch memory of *Octopus* we know that animals can still learn a simple task if all the higher centres are removed, leaving only a few thousand small cells. Take these away and the preparation can no longer learn not to draw in an object that yields pain (Wells and Wells, 1957). No doubt the activities in a group of some five thousand cells are immensely complicated. Many of the cells are probably spontaneously active or are held inactive by specific inhibition, as is known, for instance, even in groups of a few cells in *Aplysia* (Kandel *et al.*, 1969). But the situation is not beyond the range of analysis even with known concepts. At least we know that this small region of the octopus brain contains all the essentials necessary for a touch memory system. It contains certain characteristic patterns of cells, and these same patterns are repeated in the visual memory system. This, I think it must be agreed, is at least some firm knowledge about the memories of this animal.

Mechanism for Memorizing

We have now to consider how these cell systems operate. The mechanism suggested for memorizing is the switching on of synthesis by the characteristic small cells (amacrines) of an inhibitor that blocks the unwanted pathway (Fig. 2). The building up of an effective memory would thus consist of the gradual limitation of the original large number of possibilities in the nervous system.

This hypothesis has the special advantage that it enables us to understand how a memory system could have been evolved from a reflex one. Nearly all muscular reflexes are arranged in antagonistic pairs; when we activate the flexors we must inhibit the extensors. It is a reasonable hypothesis that this temporary inhibition is accomplished in the spinal cord by the production of an inhibitory transmitter substance by the small short axon cells (Eccles, 1964). Memory systems may have been evolved by prolonging the action of such cells, though, of course, much else would be needed for a complex memory. The tactile memory of *Octopus* can well be imagined to have arisen in this way from a non-learning ancestor that drew in all objects that were touched by its suckers, unless they produced pain (Fig. 2).

Amacrine cells of the type required have been little investigated because they are small and not accessible to micro-electrodes. But they are probably exceedingly numerous. Cells with afferent synapses at one point and efferent ones near by have now been found by electronmicroscopists in the tectum of the frog and in mammalian sympathetic ganglia (Sétáló and Székely, 1967; Matthews and Raisman, 1969). It is not known whether the short-axon stellate cells of the cerebral cortex could have a similar function.

The switching off of the unwanted pathways could be produced by initiating the synthesis of an inhibitory transmitter. This would, of course, involve R.N.A. and would agree with the vulnerability of the memory record to inhibitors of protein synthesis. The change might consist simply of the breaking of a link between neurons that is necessary for transmission. There is some evidence that specific connexions between cells involve the end-groups of glycoproteins, and changes in transmission capacities might be produced by the action of a single enzyme such as galactose transferase, attaching or detaching a galactose residue from the galactosamine end-group of a glycoprotein (Bogoch, 1968). This is only one of many possible suggestions.

While not directly relevant to this hypothesis it is interesting that it has recently been shown that new synaptic connexions can form in the brain if the normal ones are removed

by denervation (Raisman, 1969). Nothing is known of the functional implications in this case, but it is some of the first precise evidence that the structure of the model in the brain can change in adult life.

Primary Classifying Systems

The problem presented by the higher memory systems as compared with that, say, of an octopus is that there are so many more alternative possible actions. The higher animals can do more varied things to ensure survival. If the animal can do many different things it will obviously be worth while for it to respond to many subtle changes in the environment and to store records of the results of these actions in its memory. Our job in finding how it encodes these becomes correspondingly more complex. Fortunately an excellent beginning is made by studies of the primary classifiers in the receptor areas, such as those of Mountcastle (1957) for touch, of Whitfield and Evans (1965) for sound, and of Hubel and Wiesel (1968) for vision. In these centres there are complex classifiers that respond to particular features of input, say contours with a particular orientation. Moreover, the classifiers are laid out in systematic ways. Vertical columns in the cortex record a single feature and the features change gradually, proceeding over the cortex. In this way repeated rows provide analysis along a particular dimension (such as orientation of visual contour), separated by rows recording another dimension (such as brightness).

These cells of the primary classifiers thus play a fundamental part in the encoding systems. Their properties are certainly mainly inherited. It is still not known how the signals from these primary classifying systems are combined to allow recognition of complex patterns. Almost certainly the individual higher animal has to learn what to see or hear. The classification system is built up gradually by recording in the memory the associated patterns in which the primary classifiers have been stimulated. Pattern recognition systems have been constructed by engineers on this principle and shown to be able to learn to recognize human faces or letters of the alphabet (Taylor, 1959; Rosenblatt, 1962; Aleksander, 1969). Such systems can in principle perform recognition tasks that would be impossibly slow on the fastest digital computer. Moreover, by suitable feed-back arrangements they can be made to maintain a short-term memory after the stimulus has been removed, just as is postulated for the octopus brain.

Their potentialities, however, are still speculative. They still fall far short of even simpler mammalian brains, which have evolved ways of cutting corners by all sorts of devices that we still do not understand. One of the most important seems to be the linking together of many items of information around central themes. Stimulus cues arouse sequences of activity, which somehow serve to find behavioural answers that are appropriate.

Human Speech

Perhaps the most complex of all memory problems are those concerned with the production and recognition of human speech. Speech sounds are produced by rapid concurrent alterations of the thorax, larynx, main airways, nasal cavity, tongue, and lips, providing a modulated stream of air. The variations are produced by the action of muscles along the passage, which are, of course, essentially arranged as antagonists. We can say, therefore, that making a given sound depends on selection of alternative positions for these muscles. There are said to be 100 of them altogether, but many work in groups, of which there may reasonably be said to be 12 to 15 pairs along the airway.

In order to categorize the various sounds, the linguist

divides speech into phonemes, each of which can be defined by the presence or absence of a limited number of distinctive features. According to the analysis of Roman Jakobson 12 features are sufficient to describe all the phonemes of all languages and nine are enough for the 40 phonemes of English (see Cherry 1966). This system used by linguists is not necessarily a unique or natural one, but it does give us an insight to the number of binary selections that must be made by the brain. The number is not large for each phoneme, but, of course, we have no conception at all of how sequential selection is made so as to transmit effective messages.

Artificial Speech Recognizers

In theory it might be possible to recognize speech sounds by identifying the distinctive features, and this has in fact been attempted in artificial speech recognizers. Thus in a pioneer investigation at University College (Denes, 1959) the speech input was analysed by a bank of 20 filters to give a set of voltage outputs that reflects the energy level at each frequency at successive moments. Each sound was found to give a maximum energy in a pair of filters, and a set of recognizers for 14 selected pairs was provided. The actual spectrum of a given sample of speech was compared with these patterns stored in the machine and the best match selected by a maximum amplitude detector (Fig. 3) (Fry and Denes, 1958). Even

FIG. 3.—Schematic diagram showing the arrangement by which statistical information is combined with acoustic information in a mechanical speech recognizer. The speech input is analysed initially by means of a bank of 20 filters. From these emerges a set of spectral patterns among which it is found that the two maximum peaks are sufficient to characterize each phoneme—for example, /m/, /i/, /s/. In the case of the consonant /t/ acoustic recognition is achieved without multiplication. To these patterns are added information from the store of linguistic knowledge as to which phoneme is likely to occur at a particular moment. The most likely phoneme is thus selected by the maximum detector. Output from the space detector indicates the most likely way in which the phonemes are grouped into larger units. The decisions of the recognizer are stored in the memory and from here proceed to the output—for example, typewriter—at a constant rate. (Modified from Fry and Denes, 1958.)

such a simple system, recognizing 14 phonemes, runs into all sorts of difficulties; for instance, how often to make the sampling (what may be called the gating problem or segmentation problem). These and other difficulties have not yet been solved. In the attempt to understand them the most promising method is held by some to be not to attempt simulation by hardware and filters but to analyse the speech sounds directly by a computer programme. A recent programme gave 81% correct recognition of the phonemes of one speaker (not words), but only at about 40 times slower than actual speech

(Reddy, 1967). For greater speed, analogue and digital methods can be combined, using a system of filters for the input and a format synthesizer for the output (Denes, 1965).

Unfortunately it proves that speech cannot be properly recognized by any features of the acoustic signal considered in isolation. We recognize acoustic cues because they belong to expected phonemes, rather than the reverse. Everyone who tries to follow speech in a foreign language knows this; he feels that he could understand it well enough if only he could *hear* it. He needs more information in order to forecast what is likely to come next. The necessary information may be obtained only by considering the probability of quite long sequences of phonemes, as in words or even sentences (Fry, 1966).

It is interesting that the phonemes do not all have the same value in the organization of speech. In particular the consonants, which carry most of the information, are in the main produced by the alterations in the upper vocal tract. They are interspersed with vowel sounds, and these are much closer to the open resonances that produce the non-linguistic emotional signals of animals. Does this perhaps provide a clue to the difficult question of the origin of language? In any case it may remind us that the generation of even simple speech depends on an emotive urge to convey a particular piece of information. All speech consists of the attempt to satisfy our needs by inducing action in other people—for example by persuasion or orders, by asking questions, or by giving information. How we select the appropriate speech patterns remains an unsolved problem. The main structure of what is said is presumably chosen by activating appropriate sections of the whole action scheme or model that has been built in the brain to order one's life. Elaborate timing relations are involved in the selection of the programme for the whole speech sequence, and presumably then for the phonemes, morphemes, and words in which it is expressed. Errors such as spoonerisms show that segments as small as phonemes are selected separately and may be wrongly placed (Fry, 1969).

Association Areas

We really have very little understanding of how this is all done. In the present context the point is that the studies of language have shown us something about what to look for in the brain. Moreover, we know something of where to look. The problem of the various types of aphasia has worried generations of neurologists and is still controversial (Geschwind, 1965; Luria, 1966; Lenneberg, 1967; Newcombe, 1969). Head long ago gave a warning against "diagram making," but, so far as the layman can understand these difficult clinical problems, there do seem to be interestingly different types of aphasia following lesions in particular areas. The Russian psychologist Luria has again summarized these recently, while yet emphasizing that many parts of the brain enter into the performance of any one activity and conversely each part affects many activities.

One of the major problems is that for most of the cases examined there is no precise definition of the exact place of lesion. Nevertheless there is certainly a region in the posterior part of the left inferior frontal gyrus, damage of which affects the more motor aspects of speech (Broca's area). Injury to an area around the posterior end of the superior temporal gyrus (Wernicke's area) often produces a different type of aphasia, a difficulty in comprehending spoken speech, Head's defective comprehension. The anatomical definition of this area is not easy. The hind part of the superior temporal sulcus was called by Eliot Smith the sulcus angularis, and the region around it later came to be called the gyrus angularis. This is approximately the region of "Wernicke's area," which has also been called the area of ideational speech or indeed of the "word store." It is interesting that it lies between the association

areas connected with vision, hearing, and touch—hence "association area of association areas" (Penfield, 1966). It is sometimes said that the "angular gyrus" is characteristically well developed in man. But unfortunately it is not possible as yet to give any precise meaning to such a statement. The "area" is not defined by any sulcal boundaries, nor is it known to have any particular architectonic features. The matter is well worth investigating since it may be that it is possible to make such a distinction (see Geschwind and Levitsky, 1968). But at present the concept of Wernicke's area is clinical rather than anatomical.

Nevertheless, it is possible to understand a little of how the classification of speech sounds may be performed and the significant phonemes recognized. The auditory input to the cortex proceeds first to the superior temporal gyrus, where there are cells specifically responsive to particular sounds, as Whitfield and Evans (1965) found in the cat. Somewhere in the set of centres between this and the motor areas the selection of pathways is made such that particular combinations of active neurons in the primary auditory area excite particular combinations in the secondary auditory and Wernicke's areas. These in turn activate combinations in Broca's area, which through the motor cortex controls the airway. Lesions along this pathway produce the various types of speech defect that would be expected and, of course, also influence writing and other capacities (Luria, 1966). We may not yet fully understand the brain, but, as Horsley believed, the "horribly clumsy experiments of nature" are telling us something.

Activation of Groups of Units

Of course, it is true that we do not know what to look for either anatomically or physiologically in these or any other cerebral centres. It may be that they function by operations quite outside any currently known physiological principles. Cragg (1968) called attention to the possible implications of the fact that there are over 20,000 points of synaptic contact on a single cortical pyramidal cell. If these all came from separate sources then indeed there would be no simple neuronal chains such as we are used to thinking about. But this large number means nothing unless we know how many of the 20,000 spring from a single fibre. Anatomy has not yet been able to provide this information, but Marin-Padilla (1968) has shown that in the cortex there are climbing fibres running beside the apical dendrites and making contacts with a series of spines. Each such fibre might easily make 200 or more contacts and there might be several climbing fibres ascending as branches of a single axon. Further information is needed (see Valverde and Ruiz-Marcos, 1969).

Meanwhile I believe we can continue to think of the actions of the brain, say in speech, as produced by the activation of groups of units in ways that have been appropriately patterned by selection between initially possible alternative output pathways. Of course, the system is not a static one; there is continuous activity within it, probably much of it spontaneous and rhythmical, producing for example, first the cooing then the babbling of a young child, by its action at the various places along the airway. The system of control gradually becomes patterned, by conditioning of the motor output by the response patterns that are produced. Intonation patterns recognizable as those of questioning, affirmation, or exclamation are the first speech sounds, not yet containing individual phonemes. Then the child begins to copy its mother and others and is rewarded by approximations to correct performance. It does not have to learn all the 40 phonemes of English at once. When it says "mama" it uses only two of them, and these may be produced and recognized by very simple features, thus "m" is a softer and "a" a louder sound. When "d" is added for "dada" it simply involves producing an interruption in the sound stream (Fry, 1968). We can only

glimpse the principles by which the recognition of the significance of phonemes and the production of combinations of them grows.

It is interesting that those phonemes relating to the parents are usually the first, and it may be that the addressing system by which all the others are later classified is related to these first elements of what has been called person language (Young, 1957). The characteristics of people may provide the central features of the brain model, around which all the rest is constructed.

The suggestion is at best very vague and we do not know how the model grows, but there must be some corrective mechanisms by which the various positions adopted in the airway are limited from the success or failure of the words produced. Lord Brain (1961) quoted Froment, "It is by trial and error guided by ear that the baby learns all articulatory processes." Professor Fry and his colleagues have applied this principle in the Nuffield Hearing and Speech Centre, showing that children with very limited hearing can be taught to speak if given auditory experience sufficiently early (Whetnall and Fry, 1964).

Chomsky (1959) has ridiculed the idea of conditioning as a basis for speech learning as put forward by Skinner. There is indeed much more to language than simple conditioning, but there must be learning too. The point for us is that some at least of the skills of language may be found to depend on elimination of those connexions that produce the unwanted alternative possible combinations of positions of the muscles of the airway.

The trouble is that we have no way of conceptualizing the tremendous hierarchy of levels by which speech utterances are produced following auditory input, or following other cerebral processes. In fact not only do we not know the code of the brain, but we cannot really even imagine how it is made of sets of neurons. It may very well be that trying to build a picture of the system by considering combinations of the output of simple neurons is an entirely false clue. We have seen several hints that what is needed is some means of describing the combined operations of groups of neurons. Perhaps one useful clue to how we may proceed is the idea that the memory system of man consists not of isolated separately addressed pieces but of one unified system. This is indeed a big jump from the consideration of the switching of single mnemons. But, if there are such units, it is the ways in which they are combined that are interesting. Perhaps from earliest childhood the human memory is one unified model, to which all later learning is assimilated, as Piaget might say. It may be by further study of the features of such a model that we shall increase what we know about memory.

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