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Part I.—Original Articles

THE TWENTY-FOURTH MAUDSLEY LECTURE: THE FUNCTIONS OF ELECTRICAL RHYTHMS IN THE BRAIN.

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THE deep pleasure with which I received the invitation to deliver this lecture was tinged with dismay, for as a physiologist I am only too frequently reminded that the contributions which psychiatry has received from physiology are, in fact, almost negligible. I was therefore bound to ask myself very seriously whether I could honestly accept the honour without committing myself to stray far beyond the confines of my own subject. Finally, I satisfied my conscience by deciding that the invitation was issued in the spirit of hope rather than satisfaction, and I trust that I shall not be misinterpreting the intentions of this Royal and learned body if I feel encouraged to develop a speculative rather than a purely empiric theme. My aim is to outline the manner in which the study of brain physiology may conceivably enable us to define the physical parameters of mental experience, and the title which I first suggested for the lecture was "The Frame of Reason." Vivid though the image may be for me, I admit that the more laconic title is better, for it does at least give us a landmark and a limit to our exploring.

I confess to a childish regret for the intricate ambiguities of my first choice of title, for ambiguity seems the keynote of cerebral function. It is no wonder that until a very few years ago the regions above the mid-brain were tacitly accepted as out-of-bounds to respectable physiologists. Few text-books of the last decade devoted more than 5 per cent. of their space to the cerebrum, and of this the great bulk was conditioned reflexes and clinical curiosities. Not that I wish to disparage either the school of Pavlov or the observations of the great neurologists—on the contrary, I can feel nothing but humility that it is to these prophets that physiologists must ascribe the authorship of their apocrypha.

The difficulty and the aforesaid ambiguities have, of course, quite a simple origin; whereas in the periphery, and even in the spinal cord, an experimenter can use his customary methods to ensure that he is studying systems with only one or two variables, in the higher nervous regions he is faced by a multiplicity of simultaneous equations, and what is far worse, he cannot tell by inspection which are the dependent and which the independent variables. It is never obvious on which side of the experimental equation a term should appear, and as far as anyone knows, any term may continuously or intermittently influence or be influenced by any or all of the others.

This is clearly no easy field for the methods of classical physiology, and until the widespread adoption in recent years of electrical methods of observing the brain in intact human subjects, even the solid foundations laid by Adrian, Bremer, Dusser de Barenne, Lashley and their pupils, could not be used with confidence.

I should like to make quite clear at the outset that I do not attribute any unique theoretical importance to the *electrical* nature of the cerebral events which are recorded in the electroencephalogram. It is another handicap which we must bear as best we can, that our companion-in-arms, the bio-chemist, cannot accompany us in our raids on this redoubt—his weapons are still too slow and deadly to help us to bring back our facts alive. There still seem to be some echoes of the notorious dispute as to whether nervous activity should be considered as electrical or chemical in nature. This seems as unrealistic to me as to debate whether a torch battery should be sold in a chemist's shop or an electrician's; any chemist would be astounded at the notion that a chemical reaction could occur without electronic change and, though it is true that electricity *can* be generated without chemical reaction, as far as I know no electrophysiologist would maintain that the electrical energy of nervous impulses is generated by the movements of magnets or by friction between insulators. I am perfectly willing to accord to acetylcholine or any other reasonable candidate an importance as great as that of the compounds in a Leclanché cell—and would ask the biochemist to agree that a nervous impulse is more chemical than a lightning flash, more electrical than an oil lamp, and leave it at that for the time being.

Now, before I launch into the main topic of this lecture, the function of the rhythmic electrical activity of the brain, may I for a moment try to define in simple numerical terms, the scale of the problem which we seem to be tackling. It is said that in the human brain there are of the order of ten thousand million nerve cells. We have no *a priori* right to assume any limit to the permutations of interconnection of these units and if, in order to achieve concise results, we must really try to think and work on this fantastic scale, then clearly we had better give up trying to consider this subject as anything but a charming diversion from everyday reality. These great numbers have of recent years been rather irresponsibly quoted in comparison with artificial machines to give an idea of brain complexity and it is true that the permutations of 10^{10} set an upper limit, but, of course, it might as well be infinity. What the working experimenter wants to know is the *least* difficulty he can hope for; no one had the audacity to sail into the outer ocean as long as the world was believed flat; we can tolerate a boundless sea, but not an infinite one.

I have tried to set down, therefore, without presumption of truth, still less of finality, what may be the lower limit of brain complexity, much as an idle

Aristotelian may have done, or a list-loving schoolboy. We may add up the functional effector units—joints, glands and so on—controlled by the brain and multiply this by the degrees of freedom which they seem to possess and in this way get a crude estimate of the number of things the body can be made to do ; it seems to be only about 500. The same arithmetic applied to the receptor field gives about the same number, though for different reasons, so we can conceive of a machine with about 1,000 functional control elements which would seem to an observer to have the same capabilities as a higher animal. The list would be a good basis for the performance specification of a robot. Oddly enough I understand that the greatest number of nerve-cell patterns discerned as cortical regions is also about 500—an encouraging coincidence.

The question now arises, would such a machine be likely to exhibit any of the general behavioural properties of an animal, or would it be just a carcase which would twitch appropriately when pinched, a spinal cord ?

The answer depends upon the rules which govern the ways in which the control elements can be interconnected with one another ; a thousand reflex arcs is a reflex arc multiplied by a thousand. But if one grants that in any pair of these elements each unit may be dependent or independent or interconnected with the other in any way, the picture changes, for two elements alone can exist in any of six possible modes and 1,000 in nearly one thousand million. We have extracted a large number again, but it is the dynamic result of a permutation, not the start of one. Each of these permutations will be unique and theoretically recognizable, for the sum depends upon the assumption that all the elements can interact on one another in specific ways, though we have postulated nothing so far as to how these interconnections may be established or varied.

In order to study this abstraction more easily, models have been built containing only two elements connected with two receptors, one for light and one for touch, and two effectors giving progress and rotation, with various possibilities of interconnection. This device is in the nature of a toy rather than a tool and reminds one of the speculations of Craik and the homeostat of Ashby. To the latter it bears roughly the relations of a tortoise to a lettuce leaf, since it is mobile and exploratory rather than sessile and ultrastable. It is entertaining to consider what would happen if the homeostat were arranged to signal its stability by a pattern of lights and the wandering toys were allowed to browse on the illuminations which signal the current they require ; would the capacity of the homeostat for internal reorganization or the predatory persistence of the tortoise win the day—or would the two find a condition of mutual toleration ?

Frivolity apart, this device has yielded several valuable lessons. First, that with only two elements, behaviour is exceedingly complex and quite unpredictable when the device is operating in a normally irregular environment. Second, that, given a single inherent rhythm whereby the photoreceptor continually scans the environment, and a persistent mobility, sooner or later the whole environment is tirelessly and meticulously explored. Third, that by using a positive feedback or regenerative circuit set in operation by a tactile stimulus, the sensitivity to distant lights can be entirely subordinated to the need for circumventing immediate material obstacles, and at the same time the oscillations generated can be used to help the device to butt its way through small obstacles or sidle around large ones. Fourth, that, still with only two elements, moderately bright lights can be made attractive, brighter ones repulsive, so that the device can avoid the fate of a moth in a candle—otherwise it would merely seek the sun—yet never move too far from the lamp which signalizes its source of current. Fifth, that by connecting a source of light with the effector which is inhibited by light the device can be made to execute a specific ritual of behaviour when it detects its own reflection in a mirror or from a white surface, since in these circumstances it will set up an oscillation in a special mode, which includes the environment as a part of the reflex circuit. Sixth, by reason of the scanning mechanism already referred to, the model can avoid the dilemma of Buridan's ass or Dante's free man, "*intra due cibi*," for if two lights of equal intensity are present at equal distances from the model it will not seek a point equidistant between them and "*morria di fame*"—as many animals acting tropistically do in fact do—but will visit first one and then the other. Finally, it has been found desirable to incorporate two of the simple operations used in most nervous systems, partial differentiation and later integration, giving the device a heightened response to rapidly changing stimuli, but appreciation of steady states at a high level of intensity, combined with a short-term memory sufficient to get it well away from an obstacle before it renews its exploration or seeks its distant goal.

The social behaviour of these machines, though possibly relevant to the wider aspect of this subject, I will leave to another occasion—sufficient to mention that they display many of the paradoxes which plague our own community.

I hope that this detour into a private fancy does not seem too irrelevant to you; I would only establish, at least for the sake of argument, whether or not the physiological exploration of the mind is doomed to early shipwreck on some already charted reef. It seems to me important to realize that of the many features of the mind and behaviour which are quoted against mechanistic philosophies, there are some at least which are easily mimicked by machines. Exploration, curiosity, free-will in the sense of unpredictability, the seeking of goals, self-regulation, the avoidance of danger, a scale of values and relative importance, self-recognition, the avoidance of dilemmas, foresight, memory, learning, forgetting, association of ideas, form recognition, original creation and the elements of social organization are all within the capacity of purely mechanical devices, and the responsibility seems to me to rest now with the transcendentalists to define some further aspect of behaviour or experience for the other side to attempt to reproduce. You will notice that I have not quoted in support of psychic mechanism the large computing engines which are sometimes called electronic brains. These are not toys or pets, but tools, implements not models, and presumably the better they follow their instructions, the better pleased the designer will be, and the less they mimic the antics of the "wandering lunatic mind" the more useful they are to a mathematician. They achieve great speed, accuracy and fidelity by using vast numbers of electronic relays. That they do their sums by chattering "one and one and one and one . . ." would delight the creator of the White Queen, but their sheer speed and certitude makes them seem very unlike the only brain with which I am personally acquainted. These big adders are prodigal where our toy is parsimonious in the extreme, and I find this principle of parsimony as prominent in the world of organisms as it is helpful in the realm of ideas—Occam's razor is as sharp in the struggle for existence as it is in wordy strife, and my justification for alluding at all to the toy is not that it does anything particularly well, but that it does anything at all with so little.

If we transfer our playroom impressions to the arithmetic of cerebral elements, we must recall that the relevant comparison is not between 2 and 1,000, but between 6 and nearly 1,000,000,000, and I challenge any sceptic to prove that the ratio of behavioural complexity between toy and man is greater than 1 to 100 million.

But the construction and design of these models does more than give us perspective—it helps to give us an idea of what sort of functions we should be on the look-out for in studying the restless groping brain ; this seems more hopeful than to approach the problem from the other side, for our success in assigning functions to the electrical activity we have observed does not seem to have been conspicuous. It is easier to find a needle in a haystack if you know what the needle should look like—and that is about the scale of the matter.

You will notice that I am veering a little toward what is now called the Cybernetic discipline, that is, a fashion of thought which permits consideration of living and mechanical systems as one species in so far as they possess similar properties, with particular relation to their capacity to direct themselves toward a goal. I make no apology for this, since I believe it may help to make clear some of the observations and speculations to follow, but I need hardly say that in my use of any such operational analogy I insert mentally in every metaphor and simile the important sign "as if." We sometimes find it convenient to put the mechanical cart before the living horse when the load is too great for the poor beast and there is a chance of a tow.

What functions then, do our models and our knowledge of behaviour suggest that a brain should have if it is to be more than a super spinal cord ? On the sensory side first, you will recall that in order to give a model a propensity to explore and search for stimuli, we had to provide a mechanism whereby its single light receptor could scan the whole environment repeatedly. The internal connections are so arranged that whenever the receptor receives an adequate stimulus, its scanning is halted and at the same time the rotatory movement of the whole organism is checked, so that it progresses by a series of diminishing cycloidal movements toward the source of light. The only alternative is to provide a large number of receptors facing in all directions, with a correspondingly elaborate system of motor control. This arrangement gives no better results and is extremely wasteful of space and power and more liable to break down in proportion to the increased number of components. Applying the principle of parsimony then, we should expect to find in the space receptor sections of a brain, mechanisms whereby the sensory fields could be scanned continuously in such a way that the detailed bits of information they contain could be conveyed to a central assembly by only a few channels, there to be related one with another for appropriate action to be taken. Otherwise every single receptor unit would have to be represented by a branching chain of brain elements to connect it with all other possible elements up to the highest level—and this we know, in the case of the brain, cannot be the case. Now, the characteristics of such a scanning mechanism would be that its range or amplitude of activity would be greatest in the absence of a signal, when it would be regular and rhythmic, sweeping over the featureless central projection of the sensory organ as smoothly as the electron beam of a television camera scans the image screen for the picture elements. But on the instant that a signal appeared on its beat it would be halted, and its position at the check would convey to all other regions the relative position of the detail of sensation. When a complex pattern appeared, the succession of runs and checks would repeatedly convert a spatial pattern which was constant during the time of a single sweep—a frame, as the television engineers call it—into a series of signals on a base of time, so that all the information contained in a single parameter of sense can be conveyed on a single channel in a code of unit pulses. The economy effected by this means can be gauged by the saving in a television system, in which the scanning process transmits on a single radio channel information which would otherwise require over 100,000 channels—since the specifications of a television set are designed to fit the acuity of our own senses, this economy factor may well indicate the *lower* limit of saving which our own brains should obtain from a space-time transformation of this sort.

But what is the price of such parsimony ? First, reception speed will be limited to the frame frequency ; changes in space which occur more frequently than this or movements which cover an appreciable distance in the time of one frame will lead to blurring and distortion of the pattern. Second, intermittent signals which are shorter than the duration of the sweep but recur at about its frequency will give the illusion of movement. Third, a special mechanism must be devoted entirely to the generation of the scanning sweep, and also, if action is to be taken on the basis of information received from the field scanner, to ensuring that executive orders are transmitted to effectors only at such moments as the sensory data are complete ; that is, the outflow of centrifugal messages must be to some extent regulated by and synchronized with the time base on which the centripetal ones are coded.

Now, if we consider vision as a representative of the space analysing senses, what evidence can we find of these properties ? From the anatomical standpoint there seems to be progressive reduction in the number of units allotted to the receiving channels as we move from the retina to the projection and association areas. The psychologists have known for many years that a pattern cannot be recognized in less than about one tenth of a second, and that a motor response to a visual signal has a surprisingly long and inexplicably variable latency—from 100 to 200 milliseconds. Recently we have studied in some detail the subjective sensations produced by a flickering stimulus in which each flash is infinitesimally short on the time scale we are using, and in which there is absoutely no movement of the light during illumination and extinction. I shall be describing in some detail the results obtained with this method, but it is relevant here to mention that the principal feature described by all subjects

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is a vivid appearance of movement. Since there is no objective motion, this effect must be due to a movement of something between the eye and the integrating or " perceiving " level of the brain. And then, of course, we have the alpha rhythms of the EEG, and the cat is out of the bag—a transparent bag I fear, for the direction of my argument has been quite obvious—but I was anxious to show that the existence of some such rhythm could be predicted without recourse to electronic gadgets from facts which have been known for over a generation—if only someone had predicted it 25 years ago !

The alpha rhythm, unexpected, unwanted and disinherited by physiologists, is now familiar enough, but although it attained its majority this year, we still do not know as much about it as we should if we are to condone its origin on the wrong side of the biological blanket. That its name was bestowed by a psychiatrist and not by a physiologist may, of course, be a handicap, but let us see whether we can find in this phenomenon at least some capacity for doing useful work.

Some seven years ago we began to study this among other electrophysiological rhythms with the aid of an automatic analyser which I thought might throw some light on the otherwise mysterious fluctuations which it displays in most people, and we also hoped to discover the reason for the equally large and puzzling differences between individuals. The first suggestion which the analyser made was one which I had half expected—that the rhythm is plural. In the great majority of normal subjects the analysis showed not one component but two or three, all in the same band of frequencies, 8–13 c/s, and located more or less in the occipital region, but individually responsive to various stimuli, and, with special care, referable to distinct domains within the visual and visual-association areas. In many people—those with a classical, large amplitude, responsive rhythm—one component is much larger than the others in conditions of visual and mental rest, but even in these, when the attention is more alert, the composite nature of the rhythm can easily be recognized. For technical reasons which I need not elaborate, I was sceptical of this finding until I was assured that the components revealed by analysis could actually be tracked down and identified by residence and occupation as well as by frequency. More recently my doubt has been reduced still further by confirmation from two other sources—Cohn in America, who made exact direct measurements of frequency in high speed records, and Kensuke Sato of Japan, who analysed records by an unrelated mathematical method. Both these experimenters concluded that in most of the records they had studied, two or more components must have been present. As a working hypothesis, then, we may reasonably consider that in the transformation of a visible pattern of light into a " percept " or significant mental event, several rhythmic processes are concerned. Further, when a pattern is recalled or imagined, one or other or all of these rhythms may again be involved. At the suggestion of Golla, whose interest in these possibilities is, of course, older than the alpha rhythms, we studied the question of imagination in some detail, since it seemed at the root of the differences between individuals. This began some years ago and the early results are probably familiar to you, so I need not recount them in detail, but in general we found, and continued observation has confirmed our early impression, that in persons who habitually employ vivid and plastic visual images for mental tasks, images with all the luxury of colour depth and movement—in these the alpha rhythms were never continuous and the analyses were complex and variable—it is necessary to average the alpha analyses over a period of two minutes or so before the pattern begins to repeat in the graph. This gives some idea of the variation in the imaginary repertoire, for people of the opposite type, those who never, or only with great difficulty, employ visual images, give analyses which are almost identical every ten seconds or less. I feel that this time-function of variance may be a useful measure to apply to the analysis of personality; since it can be done automatically, it is easy to collect the information and it does seem to have a real meaning when applied to imagination. Although the parameter is a rather derivative one the measure has the advantage that it is a simple number—the shortest interval over which analyses can be made, so that successive analyses are superimposable within, say, 10 per cent. Such studies are, of course, unsatisfactory in the sense that they take little account of what the images concerned actually are; they indicate the order of richness or variety, but not the manner in which any particular mental event is related to any electro-physiological one; we shall see later that this correlation is far from ridiculous, but must be studied by a different method.

We therefore embarked upon another line of study, complementary to the first. We know that the aspects of a mental experience in the field of vision have unique properties—the beginning and the end—when a light is suddenly turned on in a dark room a subject shows not merely a blocking of most of his alpha components, but also a brief "on" effect, evoked in the occipital region. In some subjects this evoked potential is very small, as seen in the conventional EEG, but it can nearly always be identified by analysis of some sort. The latency of the evoked potential seemed variable at first, but the more careful the technique the shorter and more constant it becomes. Gastaut, using electrodes in the brain, and Cobb using a special display method, have shown that it is certainly less than 50 msec. and probably much less—in any case it is very much shorter than the time taken for the alpha rhythm to die away when the stimulus is a prolonged one and is only a small part of the total reaction time when a movement has to be made in response to the stimulus. This is important, because it means that, as predicted earlier, if a scanning process is involved in visual perception, an additional and variable delay is one of its drawbacks. In our toy model, if a light is turned on just after the scanning device has passed the position of the light, a complete rotation and extra delay must elapse before the scanning is checked and a response is elicited. It is not surprising therefore to find that though the first sign of the evoked response is constant in time, the later events are very variable both in one individual and between individuals. In our early experiments, four years ago or so, we were delighted to find—though I suppose a physiologist should have been horrified—that one of the factors which controls the latency, form and amplitude of these later events is the state of the subject's mind. Seen in its simplest form the effect is as follows: When a subject's eyes are illuminated by bright short flashes of light, the evoked response can be seen either in the primary record or in the analysis. In the latter particularly the amplitude and detail of the spectrum may remain constant over a long period. But if the subject is asked to make some mental effort which is known to involve visual imagination, not only is some alpha component blocked, but the evoked response, which may be at a frequency quite different from that of the alpha rhythms, is much reduced in amplitude and altered in appearance. In the analysis, the change in form is usually seen as a relative increase in the proportion of activity at frequencies which are multiples of the stimulus rate. This suggests that those cerebral regions which were previously responding regularly to the external stimuli are mobilized for internal service when the attention is directed to an imaginary problem—it is possible, therefore, that imagination involves the projection of an internally constructed assembly of data upon the same area as is otherwise used for the processing of " real " or external information, before the pattern can be recognized and used for the miniature experiment of thought.

We have devoted some time to studying this hypothesis and since the experiments are far from complete—there are many technical complications —my account must be tentative, but briefly, it seems that the response in the primary projection visual areas at the frequency of the stimulus is in fact at the disposal of both external and internal authorities. One may ask, how, then, is it possible to distinguish between real and imaginary events, as many of us seem to do ? It is conceivable that this is done by a signal from the very first component of a response evoked by an external stimulus—setting all the switches to " real " so to say ; if this preliminary warning is faint or missing altogether we tend to assume that the situation is imaginary. Since the elementary evoked response is small for indistinct or slowly changing stimuli there might be difficulty in deciding whether such were real or not, and indeed, who has not avoided imaginary figures on a dark night ? Of course, the other senses are commonly used to check the evidence of the eyes, but one should recall that when straight lines are made to seem curved with prismatic spectacles, the proprioceptors of the arm can often be inveigled into *feeling* them curved, and into following the over-compensation after the spectacles are removed—visual data are not merely dominant but almost dictatorial. What, then, of those people who fail to recognize that their images are different from external stimuli ? Any failure of the process whereby incoming signals are used to preclassify their consequences would, of course, give this effect, and it may be significant—if true—that in individuals with visual hallucinations the elementary evoked responses seem particularly small and in those with consistent delusions they are fantastically distorted and widely dispersed both in time and in brain-space. This brings me to another of the peculiarities of the responses evoked by visual stimuli. You will recall that a scanning system such as we suggest as a function for the alpha rhythms must have certain weaknesses. We realized very early on that the technique of using rhythmic stimuli was a powerful method of identifying those faults. The subjective impression of movement and pattern is, of course, one, but we were much intrigued to find in our earliest experiments that it was by no means only visual illusions which were evoked by flickering light. A few moments ago I mentioned that one of the effects of mental effort on the evoked responses was a change in their form and harmonic content. The peculiar thing about these harmonics is that they are not invariably—or even usually—in what are generally regarded as visual areas. They may, in fact, appear in almost any part of the brain. Study of their magnitude and distribution relative to the fundamental response is empirically useful in studying organic brain disease, because when they are exaggerated in an area which would be expected to show a fundamental response or nothing, we often find a serious disturbance somewhere nearby in the neuroanatomical sense. This, taken with their augmentation by mental effort suggests that activity at multiples and submultiples of a given primary process may be used to convey information about that process to distant regions of the brain in such a way that its provenance and destination are both included, so to say, on the label, and delays and misdirections are less likely. I sometimes consider activity in harmonic modes as a sort of cerebral gossip. The links in this argument are, I admit, tenuous, but one quite important inference from it can be made, and the verification of this has led to rather suggestive results. If the frequency as well as the pattern and position of a cerebral process are important, then it should be possible to insinuate into a receiving area what would seem to be an important message from another region merely by making the transmitting region active at the correct frequency. It might not be possible to predict what the message would mean, but if some action resulted, its acceptance could be assumed. An analogy that suggests itself is derived from cryptography. If one believes that one has discovered part of an enemy code or cipher and wishes to test one's inference, one method is to send a succession of messages to the receiving station using such symbols and patterns as one thinks one has recognized. If the recipient seems to regard these as anything but nonsense one may feel some confidence that so far at least one's assumptions are justified. If certain groups result in violent and otherwise inexplicable action one can feel even greater satisfaction.

This may seem fanciful, but in fact this is precisely what we have found to happen. In our early experiments many subjects exposed to a flickering light spontaneously described bizarre non-visual sensations and what pleased us more, whenever they did so, the brain area generally assumed to be connected with the sensations described became electrically active, either at the stimulus frequency or at a multiple or submultiple of it. Many of these finding shave already been published and I only wish here to reiterate the general inference that by activating a sensory area at the correct frequency by physiological stimuli, it can be forced to communicate with other regions in a way which suggests that the frequency and rhythm of the activity is of prime importance. If rhythmic physiological stimuli were of frequent occurrence this property would certainly be a very serious fault, but in natural conditions the eye at least is not often exposed to regularly flickering light—the effect *is* sometimes seen as a natural fault, for several patients have told us of seizures induced by accidental flicker; perhaps some would consider the specific and violent excitation of the whole body evoked by rhythmic auditory stimulation as a fault—certainly it is regarded by many as agreeable and by some as indispensable. The Greek school masters considered dancing as an essential part of education, together with music and mathematics, though they wisely prohibited the use of more than two sources of rhythm at once.

The transactivation effects which we observed at first were intermittent and apparently arose at random ; it was some time before we realized that their occurrence was not entirely haphazard but determined by the mental condition of the subject. We found, for example, that if there was a tendency for stimulation at 12 f/s to evoke a large component at 12 in the occipital region and others at 6 in the temporal and 24 c/s in the frontal area, the proportion of these subharmonic and harmonics was influenced by the attitude of the subject to the experiment. Whenever the 6 c/s component appeared there would be a subjective report of emotional perturbation and dizziness, while the 24 c/s was associated with intellectual analysis of the illusory visual patterns provoked by the flicker. Furthermore, if the subject were encouraged to abandon himself to the emotional tide, or still more if further emotional aggravation were added, in the form of embarrassing remarks or questions, the temporal 6 c/s component would swell until it out-topped its fundamental and sometimes the subject would refuse to continue, complaining of an intolerable affective state. On the other hand, if the atmosphere were maintained on an intellectual level with questions about the detail of the visual illusions and so forth, the anterior high harmonics would be augmented. In either case, when the stimulus was withdrawn both electrical and subjective effects disappeared almost at once.

Usually there was a short after discharge, lasting a fraction of a second. The significance of this after-effect will be appreciated when it is mentioned that its frequency was often not precisely that of the stimulus, for this means that our rhythmic stimuli were not merely evoking a series of discrete responses at precisely their own frequency, but were setting into oscillation a mechanism already present in distant areas, with its own frequency, domain and subjective correlate. Here is further evidence that the receiving area is, in fact, prepared to accept messages in the code presumed, and deal with them in its own way. In some cases two or more effects can be observed simultaneously : in one normal subject for example, the combination of intellectual analysis and spontaneous emotional rejection during stimulation at 13 f/s increased simultaneously a temporal subharmonic in the theta band at 6–7 c/s and a harmonic at 26 c/s in the frontal region, while it reduced the amplitude of the fundamental response at 13 c/s. The inexorability with which certain regions will pick out from a stimulus whatever aspect of it seems to suit them is illustrated by the fact that in some subjects activity in the theta band will appear in the temporal lobes—with emotional and kinaesthetic disturbance—when the stimulus frequency is within that frequency range *or* multiples of it, *or* varied in frequency in such a way that the *difference* between the upper and lower limits of variation is equal to 5 or 6 (e.g. from 10–15 or 12–18 c/s), or, when two rhythmic stimuli are present together, when either frequency is correct, or when their differences or sums are correct. Indeed, the effects of two stimultaneous sources are so peculiar and generally disagreeable that one can understand the Hellenic moderation in this matter.

Not all the variations in the response are under the control of subject or operator. Spontaneous fluctuations in mood have a profound influence in the same direction and to the same extent as short-term changes in attitude. Subjects who are accustomed to the procedure and its results soon come to be able to foretell quite accurately what their response will be from day to day, according to their subjective assessment of their spirits. Fatigue also has a great effect, which is diminished by drugs used to alleviate or postpone fatigue.

For some time we assumed that the frequency of the secondary and distant responses was strictly related to that of the stimulus, though the Russians, Livanov and his colleagues had reported otherwise. The observation that harmonics particularly, and after-discharges, when they occurred, were not precisely frequency-linked, aroused our suspicions and careful measurements have shown that there is frequently, in fact almost always, some slight discrepancy between stimulus and response rates. Even when, using a recently improved method of instantaneous frequency indication, one attempts to synchronize the stimulus precisely with that of an evoked secondary response, there is an exasperating backlash and jitter. This, of course, is further evidence of the pre-existence of the activated mechanisms, but makes it difficult to maintain an activation for long periods. Usually the response becomes slower as it increases in amplitude, but the effect is sometimes more intricate.

In order to lock the stimulus more firmly to the chosen cerebral response, various experiments have been made with electronic devices by which an evoked response could be made, so to say, to press a trigger which would release a stimulus to evoke a further response and so on. The important feature is that the delay between striking the cap and firing the charge must be controllable smoothly and over rather a wide range. Shipton has developed a system which performs this function admirably, and this has the further advantage of having two barrels, as one may say, to fire two stimuli at any interval apart. With this accessory the brain of a subject can be encouraged to build itself up into a really impressive oscillation, which in some cases, runs away and leads to a convulsive breakdown of all control. Before considering the application of this system to purely psychiatric problems, I should here digress for a moment and take you along the other route by which our present position was reached —the study of epilpesy.

The starting point was a purely practical one of diagnostic efficiency. As everyone knows, dramatic though the electrical discharges in true epilepsy may be, an obstinate proportion of confirmed epileptics have resting EEG records which are either normal or non-specifically abnormal by any criteria. This irks the electroencephalographer, and one of the earlier applications of frequency analysis was to this problem. We immediately noticed that the resting analyses of patients with a history of seizures, particularly *petit mal*, frequently looked different from normal ones even when the resting records were uninformative—there seemed to be a wide distribution of activity in clumps all up the spectrum. Of course, when we analysed during wave and spike paroxysms we obtained spectra showing many components which were harmonically related or nearly so. This is inevitable and not necessarily significant. We also showed what is again to be expected, that a convincing copy of a wave and spike pattern can be synthesized from harmonically related components in the correct relations of amplitude and phase. We went a step further and demonstrated that when the same components were generated in different parts of a model head and electrodes placed on it as for an EEG, some channels would display the wave and spike, others quite different wave forms, according to the size and phase relations as seen by each channel. Frequency analysis of such synthetic records, of course, since it takes no account of internal phase relation, gave a similar spectrum whatever the form of the recorded pattern.

All these facts suggested that one should examine the many-banded spectra of resting epileptics more closely and we therefore attempted, in as many cases as possible, to locate and delimit the various components and to correlate them with the spatial and frequency analyses during a "wave and spike" episode in the same case. The results strongly suggested that in most patients the seizure pattern was the resultant of many of the widely spaced resting components, synchronised and augmented by one of the slower rhythms. On the basis of this it was found statistically justifiable to predict the appearance of a diagnostic seizure pattern from the appearance of frequency spectra, though in some cases the prediction was not fulfilled until several very long records had been taken. I then went so far as to suggest that the liability to minor attacks was due to the unfortunate presence of a set of numerically related electrical rhythms in one brain, and the onset of a particular attack to the exact synchronization of these rhythms by the appearance of some large slow rhythmic component. I suggested that the well known effects of over-breathing alkalosis in *petit mal* were due to synchronization by the large slow waves which it evokes and which are not in themselves peculiar to epileptics; sleep too, with its slower rhythms I thought should act as a convulsant. I further predicted that any agency which evoked an adequate electrical response at a frequency which was a multiple of some of the inherent resting rhythms of an epileptic should evoke a convulsive discharge.

This was just before I decided to use modern electronic methods of visual stimulation for other purposes and it was not until we had witnessed the complexity and wide variation of the evoked response in many normal subjects that I realized how powerful the method might be when applied to the testing of my prediction.

The first subject on whom the method was tried was one whom we had followed for some years, and whose wave and spike characters had been well analysed. They always began with an augumentation of the 8 c/s resting rhythm. However, stimulation at 8 f/s was ineffective, so we tried at 16, but without result. We then connected the stimulus lamps to our first trigger device, which was a crude affair but did ensure synchronization of stimulus and response. Thanks to the patience and dexterity of my wife, it was found that when the flash was locked first to the 16 c/s component of the parietal resting record for a few seconds and then immediately to the 8 c/s occipital one, a wave and spike pattern invariably followed. This was the first patient in whom a seizure discharge was evoked by rhythmic stimulation, and it is amazing that it succeeded, because we have since found that the key to fit this lock exactly is one of the most intricate of all the hundreds we have had to fashion.

I have related this anecdote to show that the connection between the evoked responses and mental state of relatively normal people on the one hand, and the dramatic features of epilepsy on the other did not immediately impress us ; the first was a sort of experimental metaphysiology, the second a strictly practical development of clinical electroencephalography. But as the number of epileptics who responded to photic stimulation mounted toward the thousand mark in our files, we began to be impressed by the similarity between the records just before activation of a seizure pattern and the more subtle and evanescent features which we had earlier seen during " psychic " activation of normal subjects. The principal resemblance is the tendency for a discharge to appear in the fronto-temporal region at a theta subharmonic of the stimulus frequency when this is between 10 and 20 per second (Fig. 1). In an epileptic, when the stimulus is terminated in this preliminary stage it is not unusual for there to be a complaint of feeling queer and unreal, and some patients will volunteer that they have had a feeling exactly like the aura which usually precedes an attack.

That activation of a normal brain area should resemble an epileptic aura is not in the least surprising, since this may well be its nature, but we began to wonder whether the process could not be carried a step further, whether something like an epileptic seizure could not be induced in a non-epileptic by trying every possible combination of stimuli condition. I should perhaps interject here, that even in epileptics there is often only one set of conditions in which photic activation can be obtained with regularity. In some cases, for example, it is necessary to turn the stimulus on just at the moment when the eyes are closed ; there is no effect with the eyes open or closed, whether the stimulation is continuous or intermittent, but for perhaps one second as the eyelids shut, the brain is in a condition to generate a wave and spike when the flash also starts just then and is at the right frequency (Fig. 2). In other epileptics it is necessary to provide a conditioning process of flashes at a high frequency for some minutes before seeking for the effective rate of stimulation, after which the response becomes brisker and larger with each exposure. In others, again, the response fades away smoothly after half a dozen repetitions (Fig. 3). So we foresaw that even if it were possible to provoke a paroxysmal discharge in a non-epileptic it would involve tedious trial and error, since we would not necessarily have an idea of what the important factors might be.

One of our first partial successes was in the twin sister of an epileptic—partial in that she was a monozygotic twin and such individuals do often show electrical signs of epilepsy even when the personal clinical history is negative (Fig. 4). In this case the epileptic twin responded instantly at 12 f/s with regular frontal spikes and violent myoclonic jerks, though she had never had a myclonic seizure. This is one of the activation types which we recognize now as fairly common. The non-epileptic twin responded in an identical manner, at the same frequency and after the same latency, with the same subjective sensations and even more violent jerks. This was encouraging, but it was not long before a more startling case fell into our hands. In this patient there was no history of seizures, nor has prolonged observation revealed anything of an epileptic nature, though there are certain patho-physiological features which will be mentioned later. She, also, responded with extremely large frontal spikes and violent jerks when the flash frequency was between 8 and 12 f/s (Fig. 5). She found the experience most disagreeable and since she was in

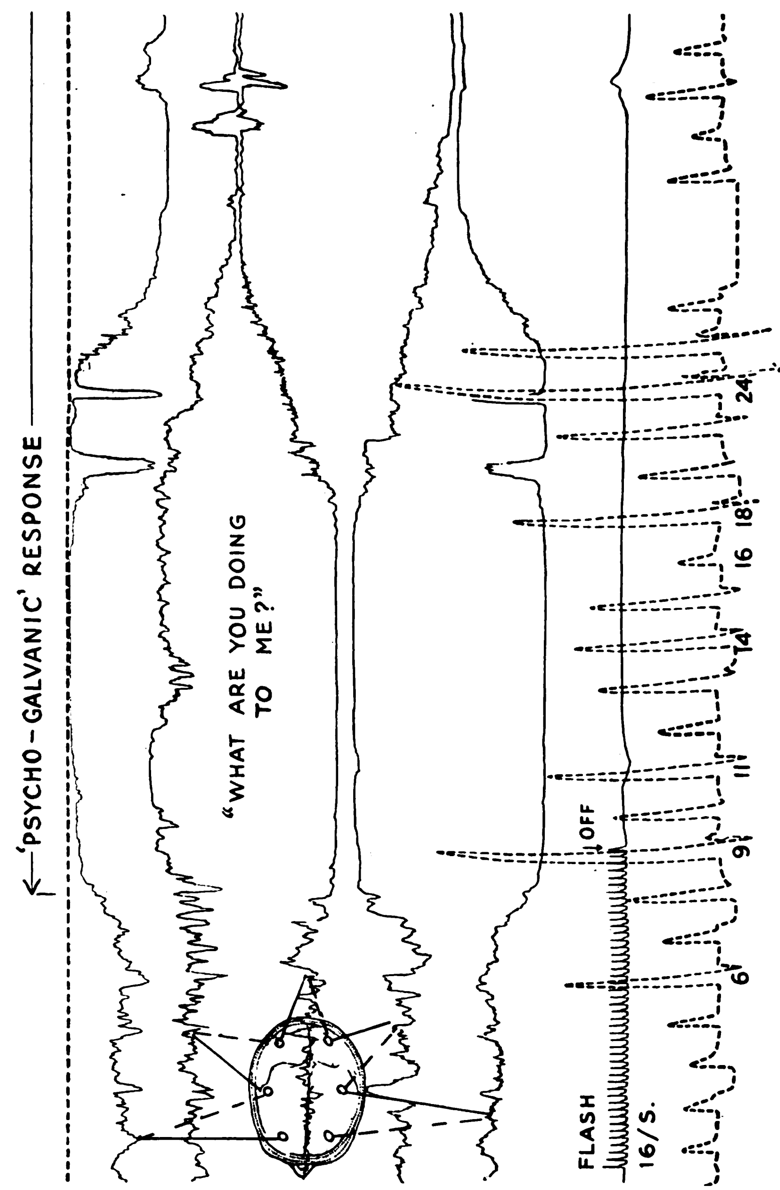

FIG. 1.—EEG and PGR (slow deflections) from epileptic patient during and after brief exposure to flicker at 16 f/s. Note complex analysis with components unrelated to stimulus frequency. After several such preliminary exposures, typical wave-and-spike patterns were evoked instead of the affective response.

the psychoneurotic category, it was repugnant to regard her as an experimental animal. However, a sufficient number of records has been collected and analysed to define the nature of the anterior cortical discharge in this

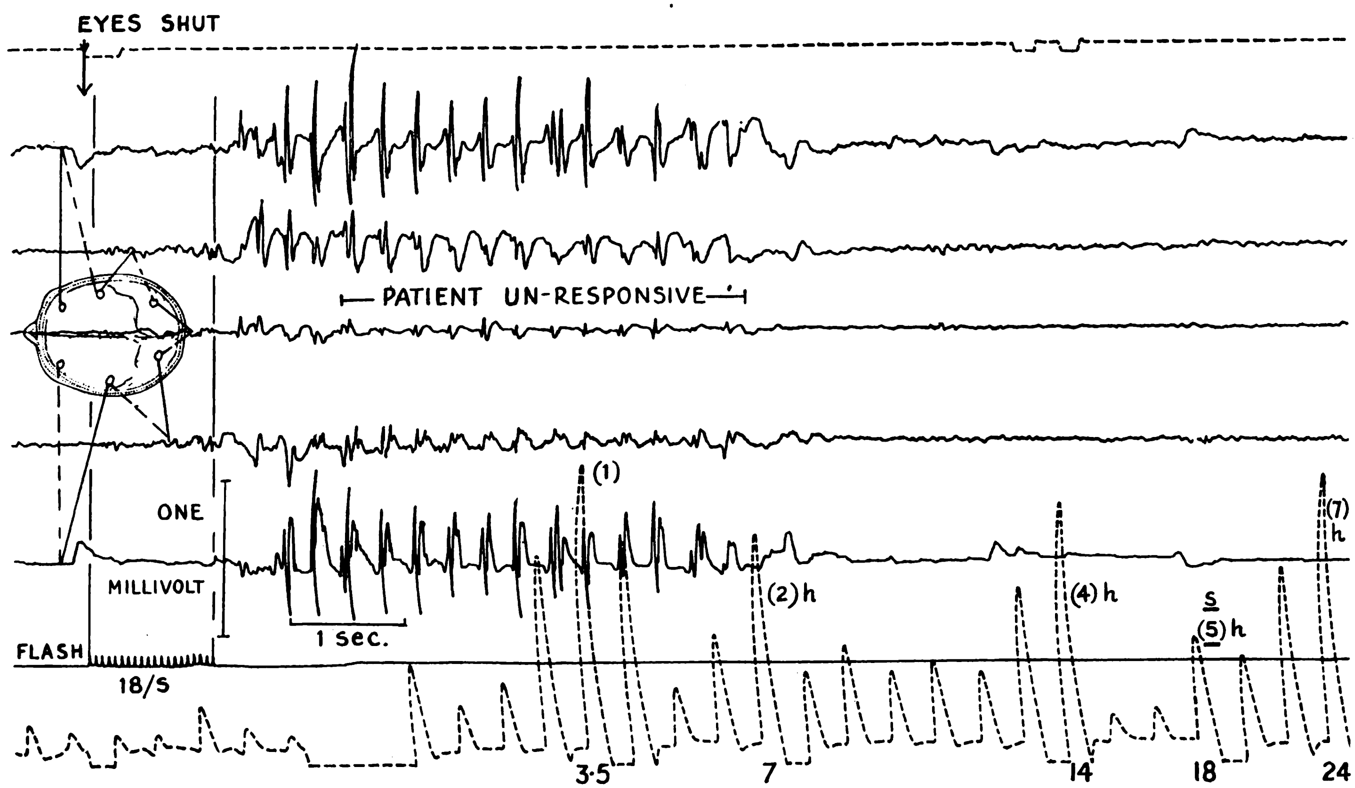

FIG. 2.—Typical wave-and-spike pattern evoked by flicker, *only* when at 18 f/s *and* synchronized with closing the eyes. Note components in analysis as near-harmonics of 3·5, including 18, although the seizure pattern and analysis begin only after the end of the stimulation. This record is representative of ten such activations obtained in the patient within a few minutes. There were no abnormalities in the resting or hyperpnoea records.

person. The first striking feature of this is that it has its own frequency, which falls as its amplitude rises, whatever the frequency of the stimulus between the limits already given—8/12 f/s. The second feature is that the discharge dies away slowly when the stimulus is interrupted, remaining visible at diminishing amplitude for from 5–10 seconds. The records are sufficiently similar to permit rough mathematical treatment of the oscillation and, technicalities omitted, this suggests that at least two major mechanisms are operative, one of frequency selection, the other of release; the only mechanical analogy I can call to mind is an alarm clock without a main spring, but a fifth second escapement which is arranged to go off every second. Since this patient was

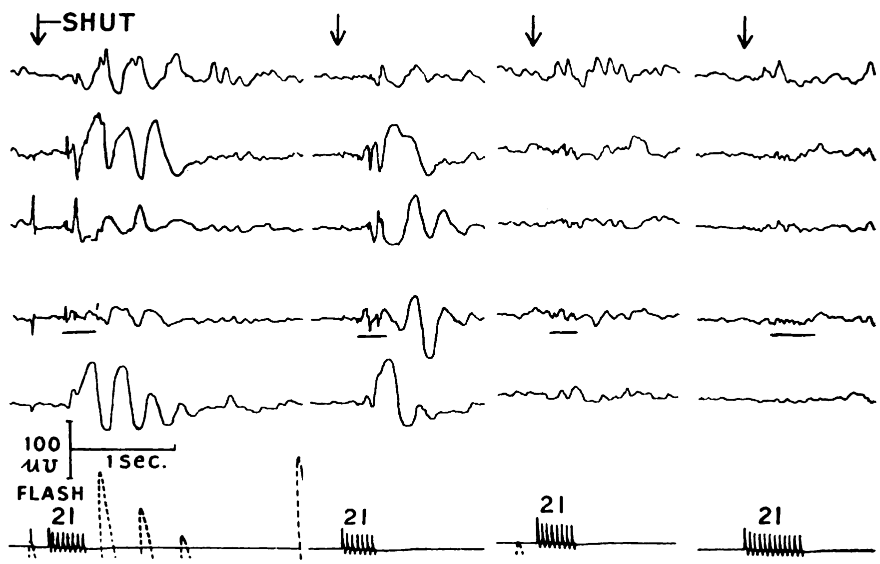

FIG. 3.—Activation of a slow mechanism by brief exposure to flicker *only* as the eyes were shut. The four exposures were made within 20 seconds and show a progressive reduction in amplitude of the secondary discharges, only the elementary ones being visible in the fourth exposure.

first seen we have observed several more without hint of epilepsy who have responded paroxysmally to photic stimulation; three give responses similar to that described, one had a typical *grand mal* seizure, others have had minor attacks of various sorts. One additional feature which has appeared is that, as in the case of the normal psychic activation, the response is sensitive to mood and atmosphere. One patient who gave frontal spikes and jerks as an out-patient had only headache and frustration as a history; after a day as an in-patient in a friendly and reassuring environment her record showed no sign of the previous anomaly; her gain was our loss. Another patient who had a history of violent behaviour, also showed spikes and jerks under flicker, but he objected to being thrown around, and tensed his muscles, which were well developed, and the cerebral and peripheral discharges were immediately abolished. The importance of a neuromuscular retroaction or feedback in these states is quite great and one should recall the experiments of Gellhorn which indicated a similar process in chemically induced convulsions in animals. There seems no doubt, therefore, that an epileptic type of discharge can be evoked in people who have never had a seizure, by physiological stimulation

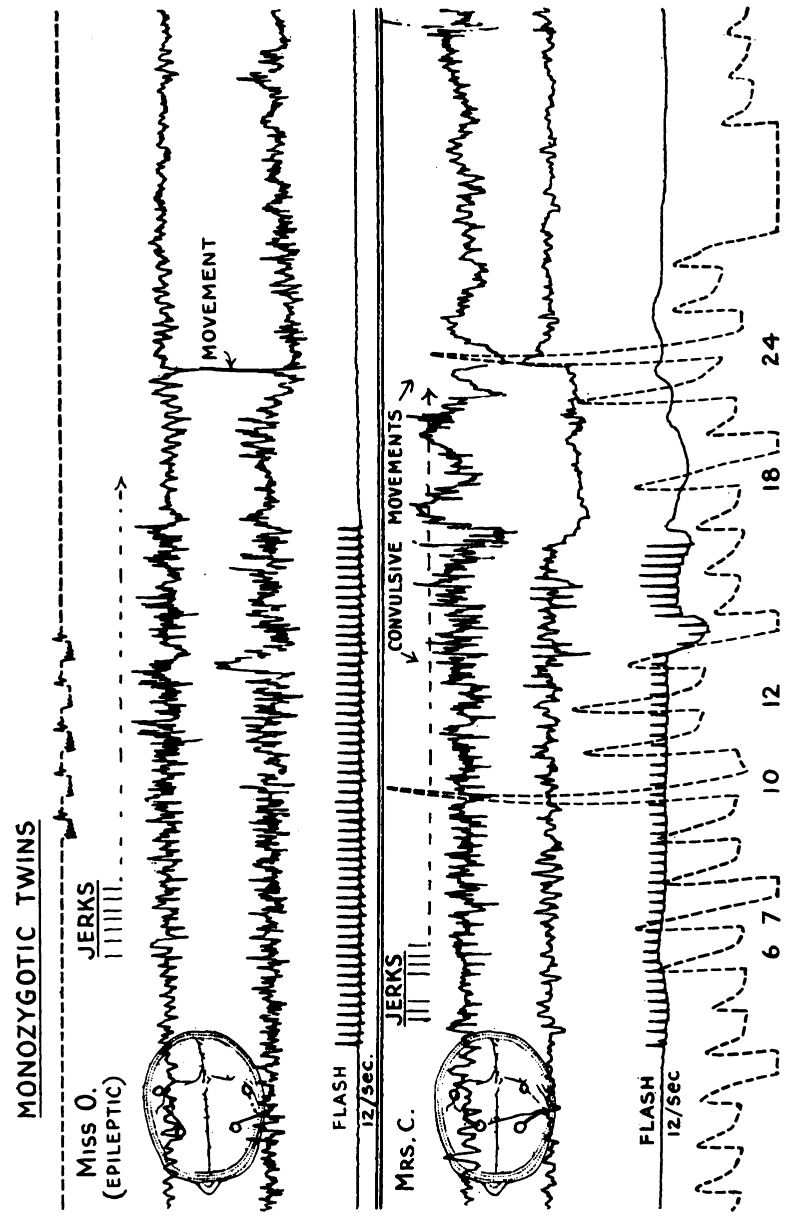

Fig. 4.—Records obtained simultaneously from two identical twins, showing the similarity of response to flicker—frontal spikes and myoclonic jerks.

in the right mode and rhythm. The only other physiological anomaly which seems to be commonly associated with this effect in sensitive subjects is some sort of hypothalamic disorder, evidenced by disturbance of sleep, water metabolism, temperature regulation, hypophyseal function and the like. A quan-

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titative assessment of this correlation would be valuable, but has not so far been within our capacity—one insuperable difficulty is that psychological treatment has important effects, and since this cannot in human charity be

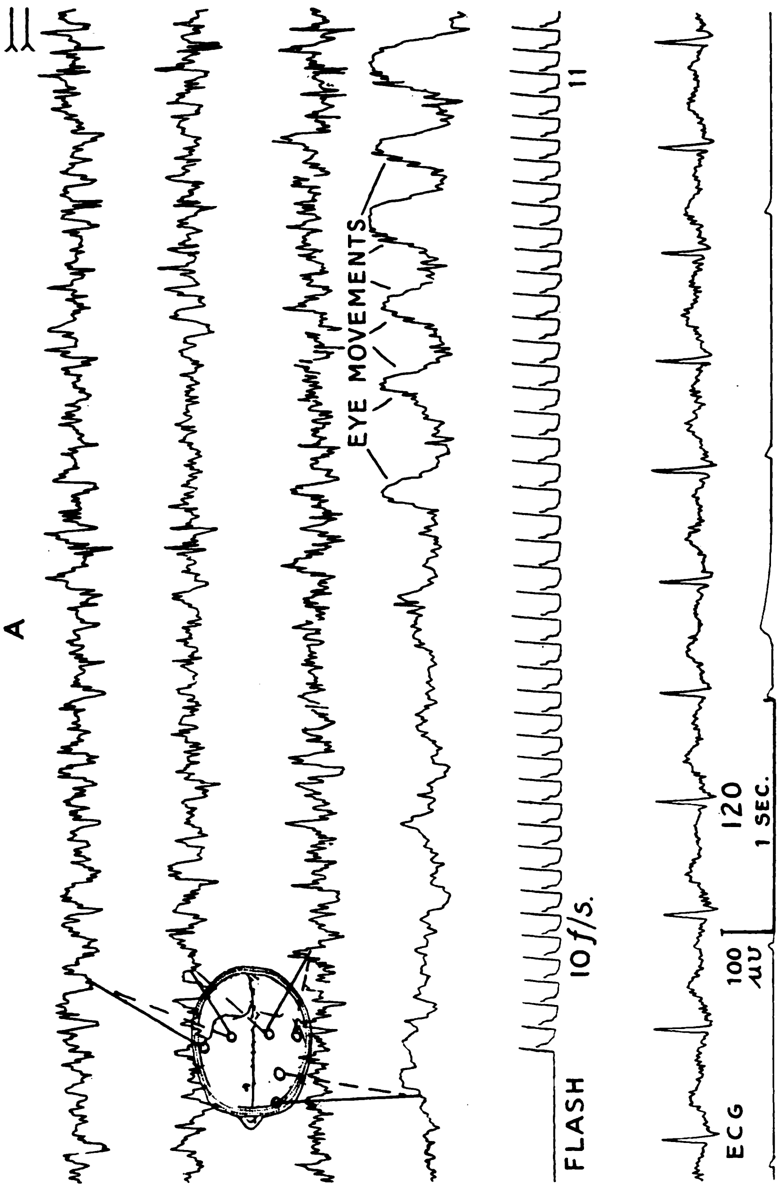

Fig. 5a.—Evocation of frontal spikes and myoclonic jerks in a *non*-epileptic patient. a. The start of the exposure, showing the first few frontal spikes. b. Continued from a, the muscular movements begin about 6 seconds after the start of stimultion. The flash rate is reduced to about 8 f/s. c. The discharge culminates in very large spikes and violent jerks, the frequency falling as the amplitude rises. The discharge persists for several seconds after the stimulus ends, and rises again in frequency as its amplitude falls. The pulse accelerates from 120 to 145 per min.

withheld, the conditions are never constant but, indeed, are deliberately changed as rapidly as possible.

Patients with a combination of epilepsy and psychic disturbance provide remarkable opportunities for physiological study, though as I shall explain later, the physiologist finds himself being drawn inexorably into the experi-

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mental circuit and usually in an undignified position. One patient with a history of occasional attacks and considerable psychological instability and eccentricity, responded at 6 f/s or multiples of this with piercing screams and

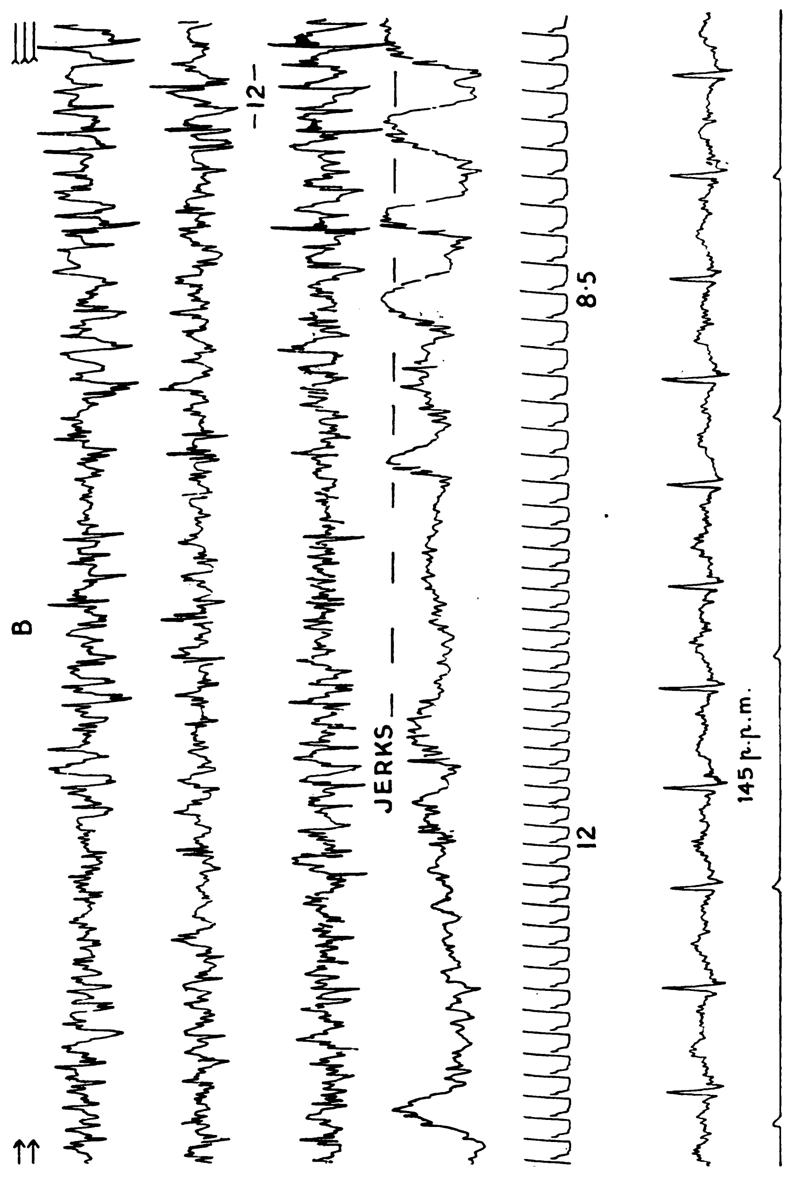

FIG. 5B.

heartrending sobs, exclaiming between outbursts that it was "perfectly all right" and she didn't mind at all really! (Fig. 6). This could have been an hysterical attack of a particularly novelettish type, but the record showed abrupt and ample discharges in both temporal lobes at 6 c/s which persisted for some time after the stimulus was terminated and the tears were stanched.

Psychological aggravation was particularly effective in this case, and so also was assuagement, for a few kind words and interest in ordinary things before the examination would greatly reduce the response; while it was of the order

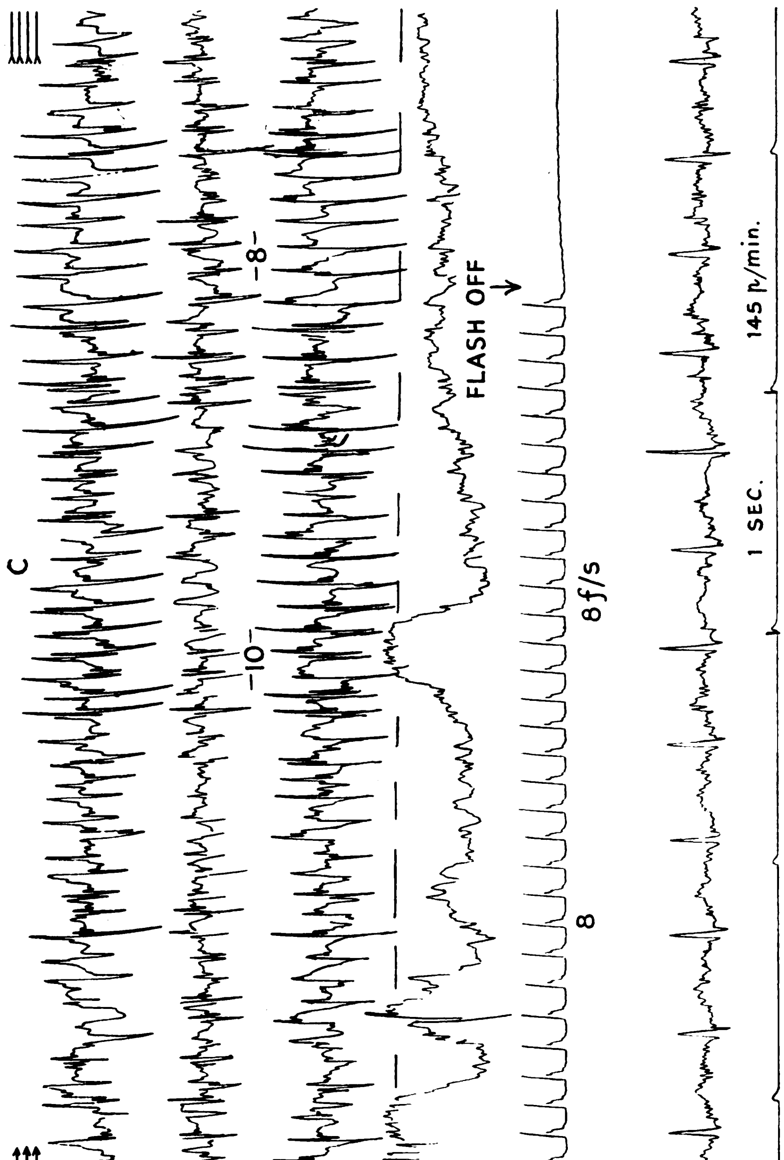

Fig. 5c.

of 200/uV when the examination was done by a woman, it was about 100/uV when done by a màn, and zero when there were two men present after a few minutes of conversation. This variation was quantitatively repeatable. This patient was able to paint vivid pictures of her sensations during the experiments; those during the early stage of violent response were sombre and asymmetrical; during an experiment, when she did not break down, they were similar to the illusion seen by most people. On a third occasion, when she had been psychologically aggravated and then mollified they were intermediate

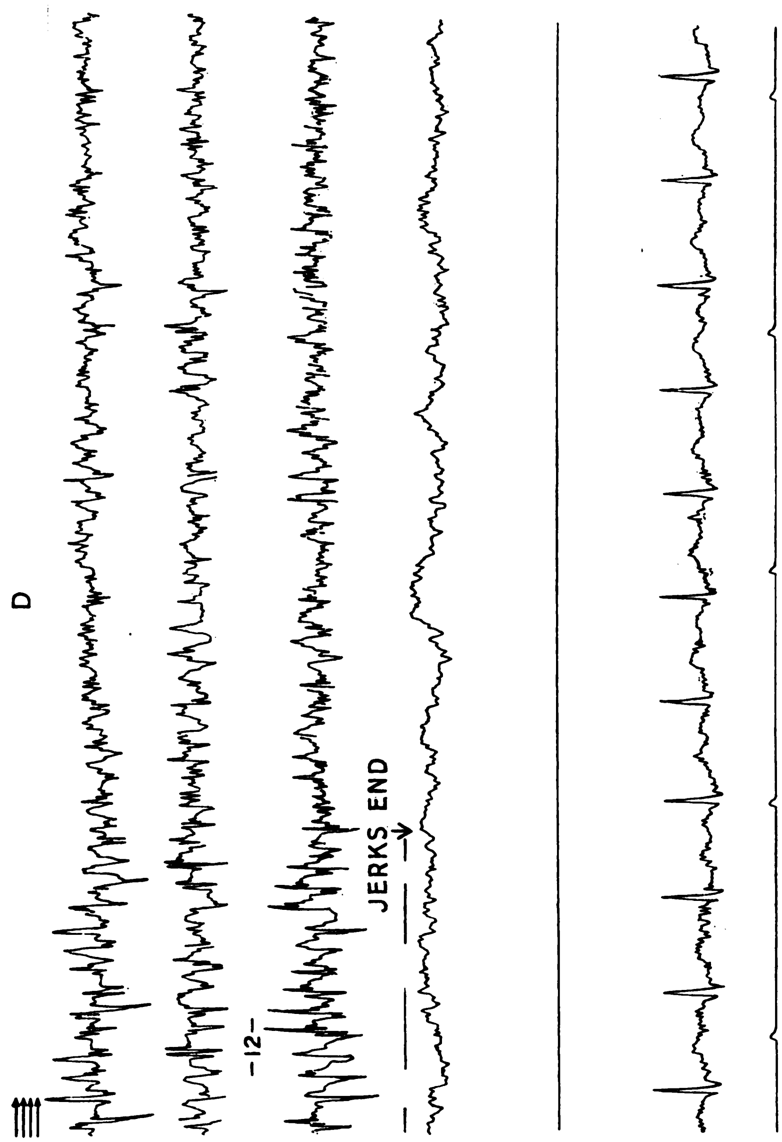

Fig. 5d.

but particularly dynamic and colourful. (I am not presenting these as physiological data, but we may have to accept such products as having the same validity as our electrical records—and possibly more immediate significance.) In this case the epileptic aspect of the activation was proved by the fact that, whenever the exposure was continued in spite of the patient's outcries, for more than half a minute or so, a characteristic generalized *grand mal* convulsion developed, heralded by a spread of the temporal discharge to the central and frontal regions. To the further psychiatric aspects I will return later.

You will have noticed, as we did, that by far the commonest of the secondary discharge areas are the temporal lobes, and of the frequencies those in what I have called the theta band are the favourite. It is *not* perplexing that the temporal lobe should be particularly accessible from the visual areas, since the tertiary and quaternary association areas are midway between the two and the rhythmic stimuli would be expected to break through the scanning mechanisms which connect these regions in a particularly forcible way. But what does intrigue us is the relation between the theta rhythms evoked in these regions by rhythmic stimuli and those which appear spontaneously in children or psychopathic adults, cases with deep lesions and so forth.

In children the theta components are exquisitely responsive to emotional stimuli, with the aid of which two or three components in this band can be recognized. With advancing maturity the effect subsides and in the normal adult, only the most disagreeable stimuli can produce any effect of this sort. In fact few experimenters have tried seriously to evoke theta activity in normal adults because to be effective the stimulus must be authentic and thoroughly offensive—one's enemies are not likely to deliver themselves into one's hands, of strangers one is unlikely to know anything sufficiently telling, and one's friends one cannot by definition offend. We searched for some time for a stimulus which would have the desired effect, and while trying a pleasant instead of an unpleasant one found an answer. The stimulus was actually intended to be gentle tickling of the face, but deteriorated into a stroking movement, which the subject found agreeable and soothing. There was no change in either primary record or analysis during stimulation, but when the stroking was *stopped* the amplitude of the theta component in the temporal analysis rose to about eight times its original value. Though the effect could be repeated as often as desired, I was not quite satisfied until I had actually seen the rhythm in the primary trace from the temporal lobes. Only a few subjects show the change as above the level of random disturbance in the primary trace, but in some it is as clear as the start of the alpha rhythm when the eyes are closed, the difference being that the duration of the discharge is usually only about 10 seconds (Fig. 7). The temporo-parietal location is easily verified either with the analyser or by the direct method, and further spatial analysis shows that in most subjects the discharge is from a region equivalent to a slice about 2 cm. from front to back and 5 cm. high from the temporal to the parietal lobes, the equivalent generator being orientated transversely and extending obliquely deep into the centre of the head. I think it is rather intriguing that we should have evidence of some mechanism that responds not to pain but to minus-pleasure—a sort of affective off-effect with a long latency—the implication seems to be that the mechanism made visible as theta activity is seeking for pleasure as the alpha rhythm may be said to seek for pattern.

But there seems to be more in these records than empirical support for the ancient scholastic doctrine that good is bad by privation. If we look at them closely we find a quite startling uniformity about each experiment. The examples I have selected are two from dozens, and I have not, unfortunately,

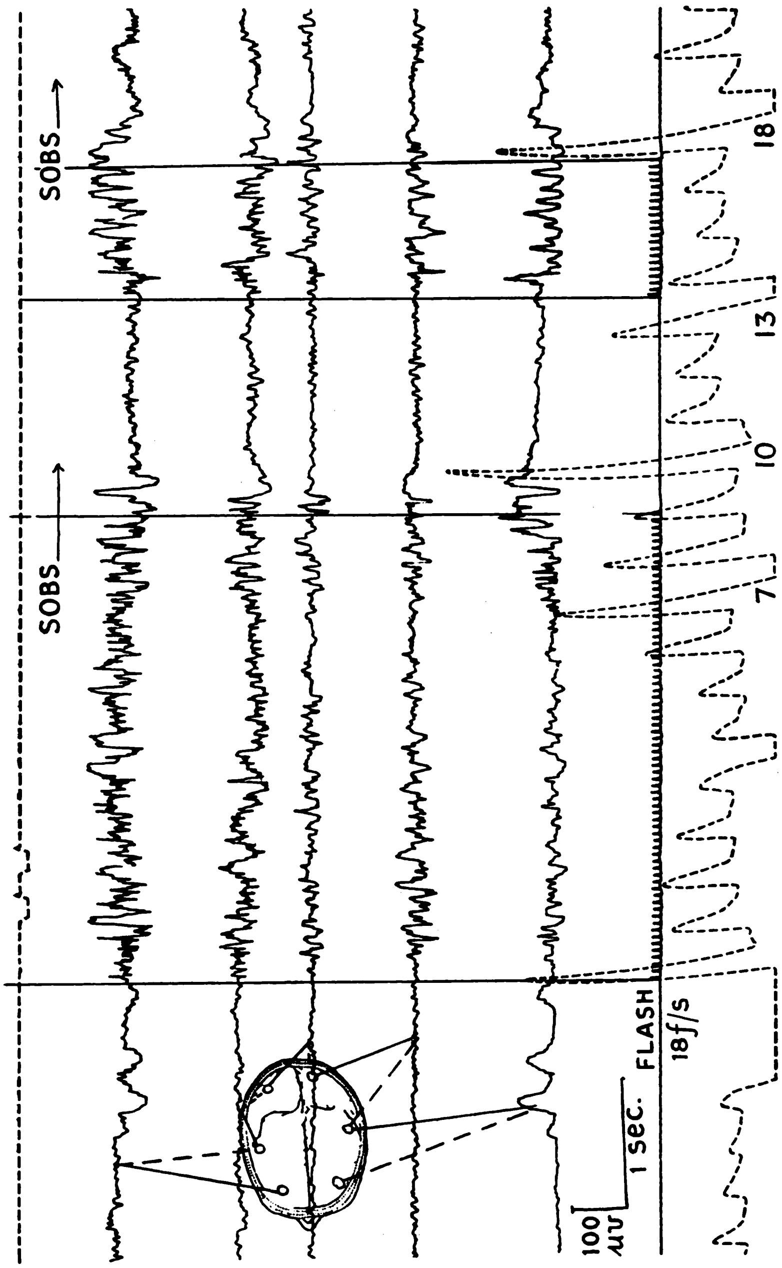

FIG. 6A.

had available during the last few weeks facilities for constructing the composite of a large number in a form fit for exhibition, but even a cursory inspection suggests that not only does the crescendo of temporal theta begin and end at exactly the same instant, but many of the details of the discharge recur in both these records, and what is more, they recur in nearly all of those taken within a few hours. Now, the only other condition in which a complex pattern

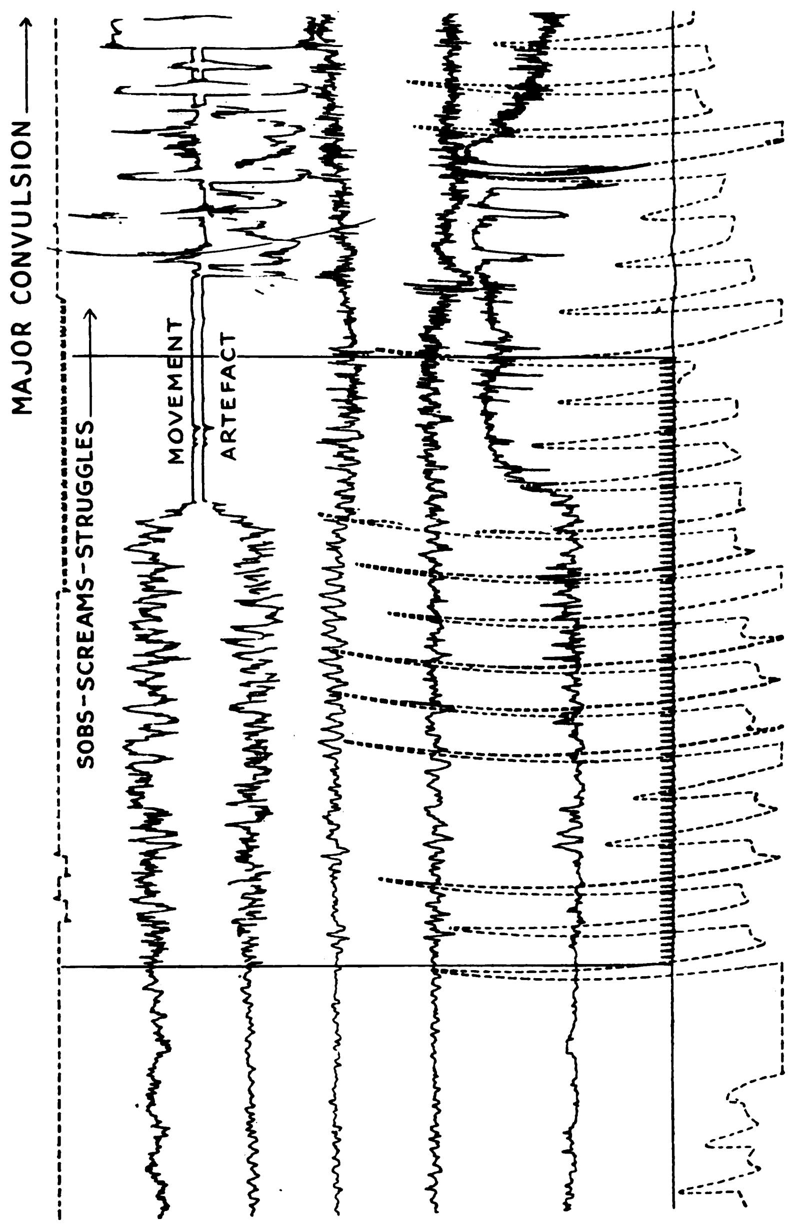

Fig. 6b.—Evocation of emotional outbursts in epileptic by short exposures to flicker at 18 f/s leading up to a generalized convulsion with longer exposures.

repeats with obvious regularity is the wave-and-spike of *petit mal*—but here there is absolutely no question of a seizure, nor, of course, does the pattern bear any resemblance to a wave and spike. Further, the pattern is far more complex and repeats not cyclically but as a whole over a period of several seconds at least. I find it difficult to avoid the implication that in such records we have before us an electrical transcript of an elaborate and purposeful *thought process*, involving the systematic rhythmic excitation and inhibition

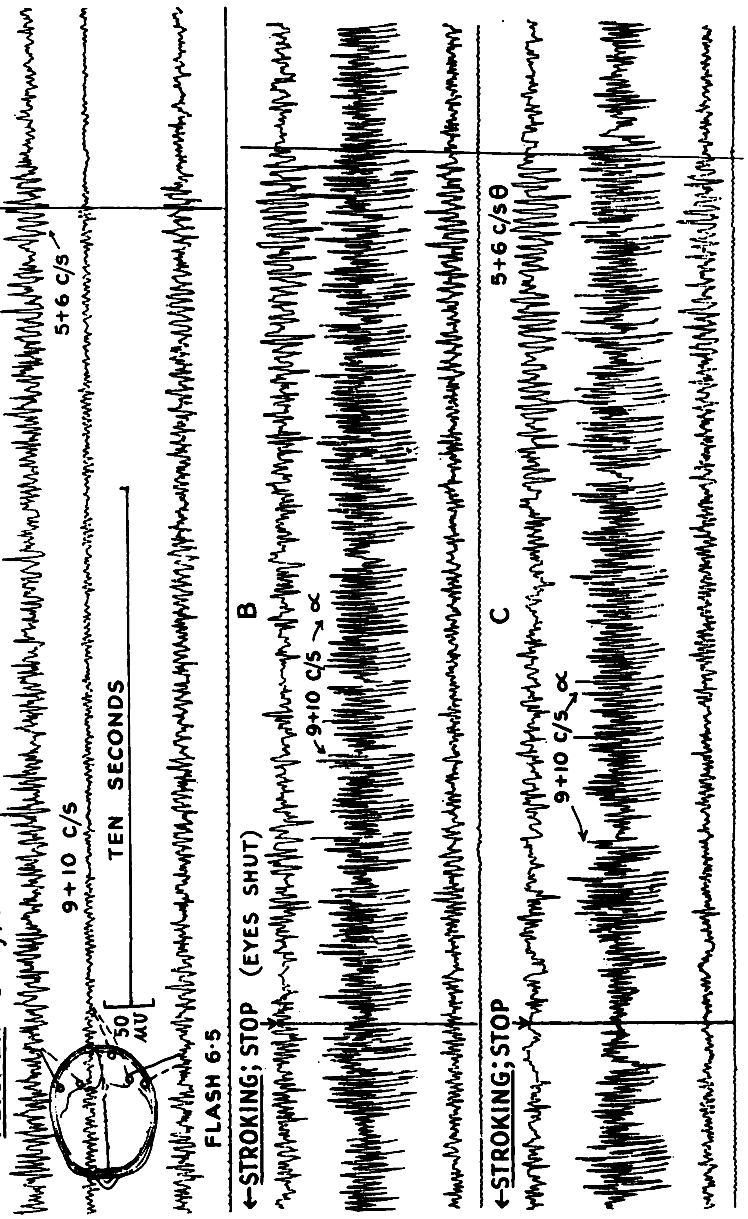

Fig. 7.—A. Evocation of temporo-parietal theta rhythm in psychoneurotic by flicker at 6·5 f/s. Note location, complexity and after-discharge of the response. B. Evocation of similar activity in same subject by termination of agreeable stimulation. Note slow crescendo of theta rhythm, its independence of occipital alpha rhythm and sudden termination 1·7 seconds after the end of the stimulation. C. Record from same subject taken a few minutes later. Note the similarity in details of the response.

of great numbers of cerebral elements in a manner which is sufficiently stereotyped for us to recognize, as it were, a single character of the great cipher. If you glance again at the record showing evocation of theta activity in the same subject by flicker you will see that although the mean frequencies are the same, the pattern is different ; there is a short after-discharge and the response frequency is not exactly that of the stimulus, so we can consider the response as an imminent mechanism, but there is rarely—except in epilepsy and those non-epileptics who develop paroxysms under flicker—anything like the degree of superimposability in evoked discharges that there is in those which develop gradually, either spontaneously or under the action of less potent stimuli.

You will appreciate that to recognize a repeating pattern against a random background is excessively difficult unless there is some fiduciary mark on which a number of samples can be aligned. Whenever there is a stimulus or a recognizable action, superimposition can be attempted. In this way, Bates has shown that if a spontaneous voluntary movement is taken as fiduciary mark, then for half a second or so *before* the movement the EEG pattern takes on a standard form; some component of the alpha rhythm seems to bear a very close phase relation to the release of centrifugal signals. By another method Richter and Kibbler have collected evidence that the moment of initiation of eye movements and other actions is similarly related to the phase of an alpha rhythm. Now you will recall that in our behaving toy we had to synchronize the effector " servo " with the receptor scanner to reduce wander and backlash, and predicted that some such device must be present in a well-designed nervous system—it seems as though this necessity has indeed not been overlooked in the central nervous system. In the case of the repetitive patterns in the theta band, however, it is not so clear that any specific effector system is being gated or synchronized, but there is physiological evidence of autonomic activity in various modes and the major component appears to be a psychic one. In the experiments with theta rhythm the commonest feeling is one of frustration, sometimes of anger, and I feel reminded of the suggestion of Craik—which is not, of course, very different from the notions of the ancients—that the function of the mind is to construct and contain working physiological models of environmental problems. It is just conceivable that some of these records may be profiles of working models of action which the subject does not quite permit himself to use. In many subjects a state of extreme tension and self control reduces the regularity of the evoked theta assemblies, while in less trammelled moments they appear more often and in more recognizable patterns, as they do in some people in that blissful drowsiness before sleep when the desirable and the possible seem to coincide without call to action.

I am increasingly disposed to use the word " temper " to describe cerebral states, as it contains the notion of time and tuning—certainly the appearance of a theta rhythm is usually a good sign of a bad temper.

There is another function which the normal rhythms may have—or perhaps one should consider this as another aspect merely of their general function—that of storage. Referring again to our model, we found it convenient to endow the machine with a short-term memory in the form of an oscillation, engendered by contact with awkward obstacles ; now an oscillation is about the most compact storage register one can imagine, since it is a process, not an object at all. Furthermore, it can be arranged to die away at almost any desired rate, and, if required, to call forth or be evoked by any similar process which has a nearby or related frequency. This provides not merely storage, but forgetting, recall by similarity, and the synthesis of "novel memories" by the superimposition of many components. It is interesting to note that if such a mechanism has the property of rapid growth, it will also tend to decay rapidly and will be less selective, in the sense that it will respond to a wider range of signal frequencies. As you have already seen, many of the evoked rhythms which we have been studying undoubtedly have some of these physical properties: their participation in at least the cruder sorts of remembering is strongly suggested by the ease with which they can be conditioned and, of course, by my earlier demonstration that rhythmic excitation at certain frequencies evokes apparently irrelevant sensations and actions which are, all the same, wonderfully consistent in any individual, but vary between individuals. Until there is very strong evidence to the contrary I suggest that rhythmic oscillation between cerebral elements as a physical basis for short-term memory is a fertile working hypothesis. Whether an entirely different mechanism must be responsible for long-term memory is another story; the vulnerability and evanescence of recent memory and of dreams contrast so much with the toughness and rigidity of long-acquired behaviour that a difference of quality rather than of quantity is indicated.

There is a growing mass of evidence that the persistence of evoked rhythms may be much longer even than that shown in the records you have seen. Significantly, the persistence is usually longest in regions remote from the primary sensory areas. In many epileptics, for example, exposure to any single frequency has only a slight effect upon the record, but if after exposure to one frequency, another related one is used, a seizure pattern will be evoked, and the preconditioning effect may last for several minutes. More striking still, Thomas has found that in some psychotic patients the response to a given flicker frequency may persist for more than ten seconds, even when the rate of stimulation is changed—here, again, the effect is often seen in the anterior frontal region.

Which, if any, of the spontaneous rhythms have a storage function cannot, I fear, yet be decided positively. The isolation of a frontal rhythm at about 8 c/s in some persons—the "kappa rhythm"—which is augmented during mental effort is suggestive, and even in apparently quite irregular records from the temporal and frontal regions analysis shows many quite rhythmic though excessively minute components in almost all the frequency bands from 4 to over 50 c/s. Many of these are extra-cerebral in origin, and I cannot feel confident about their significance until we have been able to identify them with specific states. There is a possibility that we are looking at these intimate details of cerebral economy in entirely the wrong way, rather as though one tried to appreciate a television signal by listening to it on a loudspeaker. We must cast about for the co-ordinate system which brings the picture to life and remember that though we have to communicate with one another by a succession of signals strung out in time, the thread may be drawn from a patterned web and not from a spool as our recording paper is. What an inspired image was Sherrington's—"an enchanted loom."

My thread at least is coming to end—a loose one I fear—but two tangles remain to be at least fingered. There is one group of rhythms—if it is a group

—which I have scarcely mentioned: those slow swells and surges which rock the infant, rack the adult brain. These seem at first sight to be designed solely for the gratification of the electroencephalographer, since their correlation with function seems a purely inverse one. Ten years ago, while I was trying to imagine some physiological justification for such electrical largesse, it occurred to me that we have no logical right to assume which is cause and which effect in this matter; from the point of view of the brain itself an electric field of current is antecedent to function. Further, considering that the brain lacks the three defences against injury which most other parts of the body possess —pain, lymphatic drainage and repair—it would be reasonable to find in it some special device which would immobilize and protect a threatened region and also prevent it from deluging the healthy survivors with futile and confusing signals ensuring what engineers call " failure to safety." There is other evidence, too, the wide prevalence of slow rhythms in healthy states of inaction, infancy and deep sleep, the inhibitory effect of artificial slowly changing currents, and perhaps most challenging, the strange absence of peripheral accompaniments of the enormous spike in the wave and spike of *petit mal*. In one of the records you have just seen (Fig. 2) there was a series of spikes in the motor region equivalent to one millivolt, as seen with scalp leads. Why did this huge voltage have no excitatory action whatever upon the rest of the body while a considerably smaller one in other cases with no slow waves (Figs. 4 and 5) threw the whole musculature into convulsive movement? I feel that if all the data had been presented to us at once—subjective, neurological and electrical—we should assume quite naturally that the generation of slow electrical oscillation is the mechanism whereby the organism is protected from the consequences of cerebral immaturity, exhaustion, damage and excessive discharge. That the mechanism is not always successful is no evidence against it, for, indeed, we must recognize that in the end, all individual physiological battles are lost.

Before concluding I feel bound to mention at least the basic problem of how the structure of these rhythms we have been discussing is related to the bricks of anatomy and electrophysiology, the nerve-cell and its action potential. Their rhythmicity I think we can safely assume to be evidence of retroaction or feedback of some sort somewhere. One question is, can such activity be due to what Bremer has called the " autorhythmicity " of cell-bodies and their processes, in which case the feedback would be in the cell itself, or must we postulate a true circuit, involving numbers of cell units in which the signal traverses in effect a circular path? Completely isolated cortex is not usually spontaneously active, as Burns has shown, but in certain excitatory conditions it may become so—as indeed an axone may. Conduction by summated field effects without synaptic assistance or axonic continuity again is unusual in peripheral or spinal preparations, but can occur; it does not assist the paraplegic, though it may complicate the recovery in the leucotomized patient. It would be absolutely astounding if in a structure such as the brain a signal never returned to its origin in such a way as to maintain an oscillatory discharge, quite apart from the specific evidence of interdependence between cerebral regions which has been collected from animal experiments and from man. To me the evidence on both sides seems completely convincing and, the history of science being full of true assertions and false denials, I would judge both sides victor—but to discriminate between the two effects in any particular case is a rare puzzle for the experimenter.

As to whether the activity we see in our human records is the statistical view of briefly discharging neurones and axones, we can only say that there is no evidence that it is not, and be thankful that some part of the pattern of these discharges is visible to us. In the sort of experiments I have been describing, the activity of single units seems of no greater relevance than the behaviour of a single ion in a chemical reaction; the removal or destruction of great numbers of units seems to have a negligible effect upon function. The study of brain function can only be statistical in this sense because the brain can only function statistically in relation to the environment.

I shall not venture further into the philosophical levels which were explored so expertly by my leader and colleague, Professor Golla, in the eighteenth Maudsley Lecture which he delivered twelve years ago. This lecture was a milestone in our progress and I think we can legitimately look back upon it with some sense of having travelled. I think he would agree with me that we need not assert with such finality that "The continuity of mental processes does not allow of their representation as states of mind, their interrelatedness does not allow of their separation in terms of psychological atomism. The intuitive and instinctive basis of conduct does not permit of analytical expression." This dilemma, how to study a continuous process in terms of discrete states is still with us, but I do not think we need maintain our reasonable scepticism in quite so absolute a form.

Next, one of my favourite quotations from the Introduction by Roger Cotes to the first English translation of Newton's *Principia* in 1729: "Some I know disapprove this conclusion and mutter something about occult qualities. They continually are cavilling with us, that gravity is an occult property: and occult causes are to be quite banished from philosophy. . . . These rather have recourse to occult causes; who set imaginary vortices, of a matter entirely fictitious and imperceptible by our senses, to direct those motions.

"Some there are who dislike this celestial physics because it contradicts the opinions of Des Cartes; . . . but let them act fairly, and not deny the same liberty to us which they demand for themselves . . . let us have the liberty to follow causes proved by phenomena, rather than causes only imagined and not yet proved. The business of true philosophy is to devise the natures of things from causes truly existent and to enquire after those laws on which the Great Creator actually chose to found this most beautiful Frame of the World; not those by which He might have done the same had He so pleased. . . . The same motion of the hour-hand of a clock may be occasioned either by a weight hung, or a spring shut up within. But if a certain clock should be really moved with a weight, we should laugh at a man that would suppose it moved by a spring, and from that principle suddenly taken up without further examination should go about to explain the motion of the index; for certainly the way he ought to have taken should have been actually to have looked into the inward parts of the machine that he might find the true principle of the proposed motion. The like judgment ought to be made of those philosophers who will have the heavens filled with a most subtle matter which is perpetually carried round in vortices."

Well, the relation of vortices to mental states is almost as inaccessible to us as the heavens were to Newton, but I think he would agree that if one cannot take a machine to pieces to see whether its rhythm is from a spring or a weight, one might reasonably start by shaking it and even perhaps end by turning it upside down.

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