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**A Method of Recording the Moving Electrical
Potential Gradients in the Brain:
the 25-Channel Bavatron and Electro-Iconograms**

By

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A Method of Recording the Moving Electrical Potential Gradients in the Brain: the 25-Channel Bavatron and Electro-Icnograms

JOHN C. LILLY

AS THE central organ of the body for reception of data from the external world, the computation, correlation, and storage of those data, and the preparation of further data for action in the external world, the brain and its activity are of great interest. Our interest is matched only by our lack of many essential data. Despite about 500 years of work on the anatomy, physiology, pathology, and psychology of the central nervous system, we still do not know fundamentally how the organ operates. Since about 1875, it has been known that the brain produces electrical potentials; since about 1930, it has been known that there is at least one electrical sign invariably accompanying each and every action of each part of the living nervous structure. Since 1930, correlations have been sought between the electrical patterns produced and the concomitant physiological, behavioral, and subjective variables observable at the same time. A host of isolated facts about correlations between these four sets of variables plus the fifth set of place and structure in the central nervous system (CNS) has been accumulated in the past twenty years. However, there are a number of missing links in the host of facts: we cannot as yet get enough data simultaneously from enough points dis-

tributed throughout the brain to follow and record what the whole structure is doing at each significant instant of time. The work that follows is a crude first-approximation attempt to begin to record from a large enough number of zones simultaneously so as to begin to see some of the 2-dimensional cross sections of the 3-dimensional patterns of the activity in the brain.

STRUCTURAL FACTORS

To get some perspective on the complexity and size of the problem, a few numerical data from neuroanatomy are in order. Let us consider the cerebral cortex, the great sheet extending over the "outside" of the rest of the brain and taking up a little less than one half of the volume of our cranial cavities. In man, this sheet, if laid on a flat surface, would occupy a square about 18 inches on a side in a layer 1/10 of an inch thick; two-thirds of this area is hidden within folds (sulci and fissures). The number of individual functioning units (cells) within the sheet is 13 billion, approximately. Each cube of the sheet, one millimeter on an edge, contains 40,000 cells. A square piece one centimeter on an edge has a "population" equivalent to that of New York City.

In theory, but not in practice, each of these cells and their conductors, at a given instant, can have a potential field distribution different from all the others. With electrodes larger than the sizes of the cells and their average intercell spacings (25 microns or 1/1000 inch), the field "seen" will be a composite "superposition" field from many cells. If the superposition field shows simple figures or traveling forms, we can say that the cells are operating as interdependent units in the brain. As is shown in the following, simple figures of activity are found in brain areas of about one square centimeter; hence groups of approximately 40,000 cells are probably fired in a se-

quential and/or synchronous fashion. What we see will depend directly on the electrode size, the interelectrode spacing, and the number of electrodes. It is to be emphasized that our present studies are on the behavior of large populations of cells, not on the activities of individual units.

Our major technological problem is that of electrodes and their development. The cells of the brain need intact blood supply (every cell is within about 25 microns of a capillary), and undistorted shape and spatial relations with neighboring cells. Up to the present, we have devised arrays of electrodes which change these factors a minimal amount while picking up the activity at the presented surface of the brain (cortex). As yet we have not devised a satisfactory array for recording from the depths of the brain without causing bleeding and without large structural distortions of the tissue. Satisfactory penetrating arrays of electrodes probably can be developed by future work.

For obvious reasons we are limited to animals (not man) for our development work. To gain a perspective on animals other than man, Table I shows the comparative data on the cortex for man and animals. The whale brain (22 pounds in weight) is also given as example of a brain larger than that of man (3.3 pounds in weight); for technical reasons, there are no neurophysiological data available on this species.

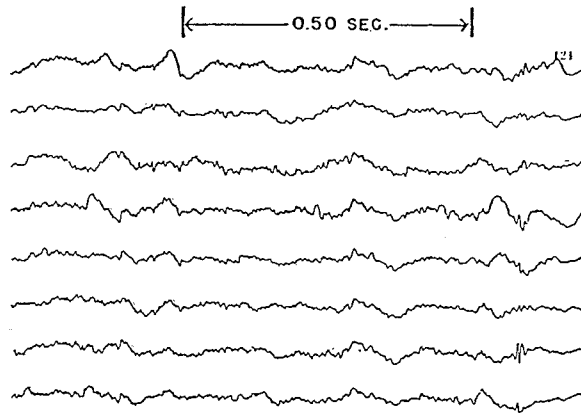
To cover just one surface of the whole cortex of each of these species with electrodes two millimeters apart requires the following numbers of electrodes: whale, 250,000; man, 63,000; monkey, 2,500; cat, 500; lemuroid, 100. In calculation of these numbers it was assumed that we can place electrodes on the areas hidden in sulci and fissures; we cannot do this as yet. Stated in another way, the present array (eight by eight millimeters, 25 electrodes), covers only the following fractions of the total cortical surface of the various species as follows: whale, 1/10,000; man, 1/2,500; monkey, 1/100; cat, 1/20; lemuroid, 1/4. To cover the structures not on the surface at 2-millimeter intervals, we would need approximately three times as many electrodes as those on the cortical surface for each species. These calculations show the magnitude of the problem of covering the brain, inside and out, with electrodes at 2-millimeter intervals; at 1-millimeter intervals, eight times as many electrodes will be required in each case.

But what is the population of cells between electrodes in each spacing (two and

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Figure 1. An ink-writer record of the electrical waveforms picked up on the surface of the human brain at operation



The electrodes are silver balls, 1 millimeter in diameter, spaced about one centimeter apart, distributed over the presented outer surface of the parietal lobe in an approximately square array. Each electrode drives one ink-writer through one-half input of one differential amplifier; the other half of each amplifier input is connected to all others, and the common point "grounded" on the skull. Between electrodes there are sulci interrupting the continuity of the available cortical surface. Some artifacts, due to slight movements, show as synchronous slow waves in all leads. This is a sample of the usual waveforms picked up directly from any unanesthetized mammalian brain—rabbit, cat, dog, monkey, chimpanzee, or man. The frequency distributions of observed wave forms are from about one cycle per second to about 50 to 60 cycles per second (instrumental pass-band limits) (reference 1); the potential differences commonly encountered are from a few microvolts to two or three millivolts, peak to peak. The wide differences between these eight leads is to be noted. Except for the artifacts, each lead produces a record which looks independent of the others, except for rare waveforms

one millimeters)? The cube bounded by eight electrodes contains 320,000 cells at the 2-millimeter interval, and 40,000 cells at the 1-millimeter interval. Therefore, even with such good coverage as would be furnished by one million electrodes (1-millimeter interval) in man, each electrode is still affected by a population of, say, 5,000 cells.

With these data in mind, some of the neurophysiological aims of this project can be formulated; we wish to find out, for each major division of the brain, how small a zone must be "watched" by each electrode of our array to give the essential information as to how that division functions. For example, in the visual cortex (area 17) do we get essentially the same picture with 1-millimeter intervals as we do at, say, 0.05-millimeter intervals between electrodes? In other words, how many cells fire synchronously during activity of this division—5,000 or 9?

TIME FACTORS

It is probable that the electrical activity of the brain contains important information in the time scale range from about 10^{-4} seconds to the life span of the animal. However, during a given short observation period of, say, 30 hours, with

100-micron diameter electrodes, most of the information which we now know something about is periodic and is contained in a frequency band from about one cycle per 10 minutes to 10,000 cycles per second. The highest repetition rates are those in the population of acoustic neurons: though each fiber can fire only at a maximum rate of about 300 per second, the superimposed potentials from many fibers can give an envelope modulated at about 10,000 per second.² The slowest waves so far recorded with direct-coupled amplifiers are those on the cortical surface.³

The pass band receiving most of the attention of present day investigators is from about one cycle per second to about 100 cycles per second; this band contains most of the observable waveforms of fairly high amplitude seen with macroscopic electrodes on the cortical surface (Figure 1). In the conscious human, the maximum amplitude band is in the 8 to 14 cps. region.¹ The range of amplitudes encountered is from a few microvolts to about one millivolt, though some waves as high as 50 millivolts can be produced by certain drugs on the cortex.⁴

With these facts in mind, the present electrical equipment was designed to concentrate our first efforts on the band of frequencies from about one cycle per second to about 300 cycles per second. As will be seen later, our present upper frequency limit is not determined by the

amplifiers or the output transducers: it is limited by the camera to something less than 60 cycles per second (instead of the potential 300 cycles per second of the rest of the equipment).

MULTIPLE-CHANNEL AND MULTIPLE-RECORDER SYSTEM

The system chosen for our work is a separate channel of amplification for each electrode and a separate recording element for each channel. This system was chosen for the following reasons:

1. The state of development of the art of single channels is sufficiently advanced to allow rapid design and construction techniques to be applied.
2. The components are readily available in sufficient quantity to allow selection of critical parts for best performance and easy replacement.
3. More channels can be readily added to an existing system without major changes in design.
4. By using no switching or scansion or other time-division techniques, the usable over-all bandwidth is limited at the recorder, a motion picture camera, by the frame rate employed (up to about 350 frames per second) (Figure 2).
5. No low-level switch elements, scanner, or electron-image tube were available for the low voltages and low frequencies required.
6. No outstanding saving in number of components could be predicted by using high voltage level switching (after amplification by separate channels) into a single recorder (cathode-ray tube) for the number of channels planned (25).
7. Glow lamps of high intrinsic brilliance and rapid response were available to use as recording elements.

Present Apparatus

For recording the 2-dimensional cross sections of the electrical activity of the cortex, we use 25 channels of amplification with a single input electrode and a single intensity-modulated glow lamp per channel. The electrodes and lamps are in two corresponding square (five by five) arrays, one on the brain, the other in the

Table I. Approximate Cortical Dimensions and Cell Populations in Different Species*

Species	Volume, Cubic Centimeters	Surface, Square Centimeters	Equivalent Square, Inches on Side	Thickness, Centimeters	Number of Cells, Billions	Hidden Fraction of Surface
Whale.....	3,000	10 ⁴	39	0.29	120	?
Man**.....	320	2.5 × 10 ³	18	0.25	13	2/3
Monkey**.....	140	10 ²	4	0.2	0.8	1/2
Cat**.....	2.5	20	2	0.1	0.1	1/3
Lemuroid**.....	0.6	4	4/8	0.15	0.027	1/10

* Cell concentrations are about the same in all species: 40,000 per cubic millimeter; intercellular distance 25 microns.

** Calculated from data of P. J. Harman, *Journal of Comparative Neurology*, volume 87, 1947, pages 161-8.

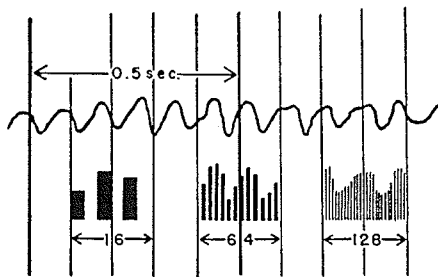


Figure 2. Effect of time division of a single EEG (electroencephalographic) channel

The upper record is of an ink-writer recording of a train of "alpha" rhythms from the skull of a human. The lower rectangles are the result of time-dividing the upper record, with an "off to on" ratio of 0.5, and of integrating the waveform during the "on" phase. The rectangle height is the final value of this integral. The results are shown for three pulse repetition rates: 16, 64, and 128 times per second. This record shows that if the EEG amplifier is used to intensity-modulate a light source, and the light is photographed with a motion picture camera, that at least 128 frames per second is needed to record the EEG and electrocorticographic waves in order to get a fair reproduction of the waveforms on the film

camera field. Some of the details of the apparatus are given in Figures 3, 4, 5, and 6. The name "bavatron" was selected from the initials of the phrase "brain activity visualization in areas" plus the suffix "tron" meaning a device. The records of the 2-dimensional patterns of potential difference which result are called electro-iconograms, or "EIGs," for short.

ELECTRODE ARRAYS

Figures 4 and 5 give the details of one type of electrode array used. Another type, in which the skull is kept closed, has also been developed. The closed skull technique allows the brain to be kept in the best condition for days and possibly weeks at a time. Our "implanted" array consists of a stainless steel (type 316) ring screwed into a 3/4-inch diameter hole in the skull, a lucite electrode holder fitting snugly into the ring, and a square array (five by five) of 0.9-millimeter diameter glass tubes sealed into the lucite at 2-millimeter spacings. The glass tubes communicate with 2-foot lengths of Tygon tubing which carry an electrolyte solution. The other end of the plastic tubes fasten to 25 AgCl-Ag half-cells built into a 4- by 4- by 1/2-inch lucite block. The half-cells are connected to the amplifiers by simple lead wires. With this later array we have made observations on cats (auditory cortex) for intervals up to four days. At the end of the four days, the

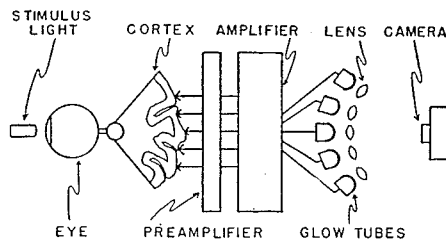


Figure 3. General plan of the present apparatus, the bavatron

The electrodes are shown as arrows on the cortex. This is a cross-sectional view from "eye" to "lens"—there are four additional "layers" of all elements behind this layer, giving a total of 25 electrodes, preamplifiers, amplifiers, glow tubes, and lenses for one brain and one camera. The electrodes are distributed in a square (five by five) array on the cortex, the glow tubes and lenses in a corresponding square array (five by five) in the camera field; each electrode drives one glow tube through one amplifier. The varying light intensity of each glow tube is recorded intermittently by the motion picture camera as a series of circular images (of the lenses), whose density varies with the input potential. During the time the shutter is open (4.5 milliseconds out of a cycle of 7.8 milliseconds at 128 frames per second), the film "integrates" the wave form of the light variations (see Figure 2). The electrodes are shown in a diagram in Figure 4; and in a photograph in Figure 5. The preamplifiers and amplifiers are shown in a block diagram in Figure 6

animal and the cortex were in a condition as good as at the start; the beginning and end records are indistinguishable by our present standards. The records shown in the later figures are samples from some 3,500 feet of movie film taken with this array. Figure 8 shows the hole in the skull and the technique of locating the electrodes.

The electrical resistance of the electrodes in Figures 4 and 5 is about 600 ohms at 1,000 cycles per second. This is sufficiently low so that pure resistive (thermal) noise does not disturb our recording. But other "noise," such as that due to pulsations of the brain (with an opened skull) with heart and lung action can be sufficient to overload the amplifiers at full gain. With care, these artifacts can be avoided; however, the "closed skull" array eliminates the artifacts by not allowing the brain pulsations to occur at an amplitude sufficient to cause artifacts.

The electrical resistance of the "implanted" array is 50,000 ohms per electrode, which is also low enough so that resistive noise does not interfere. Most of this resistance is in the electrolyte conduction path between brain (pia) and the half-cells, whose resistance is less than 100

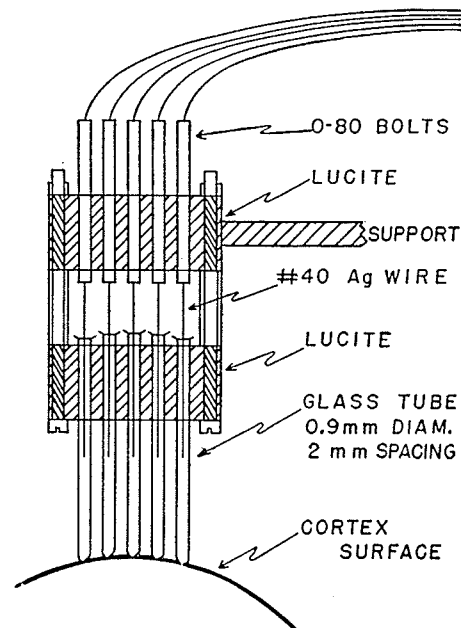


Figure 4. Cross section through a row of five electrodes in square array of 25 electrodes

This array was designed for small-area surface pick-up with minimum pressure on the exposed brain surface. Each glass tube is free to slide up and down a distance of about one centimeter, under gravity; each one exerts a total force on the cortex of about 17 milligrams. The conduction system is: cortex, pia, 0.1-millimeter-diameter hole in the end of the glass tube filled with cerebro-spinal fluid, glass tube filled with cerebro-spinal fluid, AgCl-Ag wire tip, number 40 B and S Ag wire (enameled with 20 coats bakelite varnish), 0-80 bolts, and the lead wires to the amplifier input. The insulation system is glass, lucite, bakelite varnish, and Tygon tubing over the tops of the 0-80 bolts and over the lead wires. The glass tubes take up positions which follow the curves of the cortical surface. A photograph of this array is shown in Figure 5

ohms. We have not yet investigated the reactance components of the impedance of these electrodes, but expect that it is negligible from one cycle per second to 100 cycles per second.

AMPLIFIERS

Figure 6 gives some of the details of the amplifiers used. The 12SN7GT and 12SJ7 tubes are aged 200 hours with applied voltages of the values used in the amplifiers; they are then selected for minimum noise, minimum microphonics, and best differential action. A yield of about 20 per cent is obtained from a population of commercially obtained joint Army-Navy tubes.

Twenty-five variable plate-to-cathode resistors (300 kilo-ohms) are used to equalize the transconductances of all stage 1 tubes. So far, we have been able to achieve a common mode rejection ratio

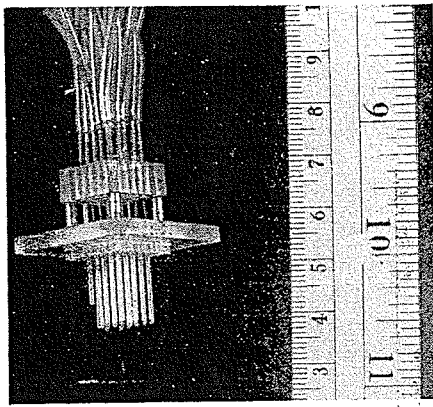


Figure 5. A square (five by five) array of 25 electrodes

This array is diagrammed in Figure 4. The tips of the electrodes fill a square on the cortex eight millimeters on a side. One electrode is pushed up to show the action of the glass tubes. The array holder, not shown, clamps to the upper lucite block. The scales are in centimeters and inches. The lead wires are silver-soldered to the upper ends of 0-80 bolts; the Ag wire is lead-tin soldered to the lower ends. The upper lucite piece is threaded for the 0-80 bolts. The glass tubes fill, and stay filled in a saturated atmosphere, by capillary action only.

of only about 100 to one with this arrangement in the amplitude region of interest. We can probably do better than this with extremely careful adjusting.

The over-all pass band is from one cycle per second to 750 cycles per second at the six decibels down points. The phase shift is 90 degrees at about 350 cycles per second.

The full-scale signal at full gain is 100 microvolts at an output current through the glow lamp of 30 milliamperes. The residual hum level with the inputs short-circuited to ground is less than 10 microvolts.

There are 25 3-step (full, 1/100, and closed) gain controls between the first cathode follower (CF) and stage 2. There are 25 6-step (full, 1/3, 1/100, 1/1000, closed) gain controls between stages 2 and 3. These controls facilitate running down bad tubes, soldered joints, and so forth, in trouble-shooting the equipment by isolating the various stages.

Because of the action of the cathode resistors common to each stage in the 25 channels, each electrode potential is seen only as a difference from the mean value of all the others. This action results in rejection of signals common to all 25 electrodes at a given instant, within certain limits. Such a "differential" signal is seen as a brightening of a glow lamp when "negative" with respect to the mean, and a darkening, when "positive."

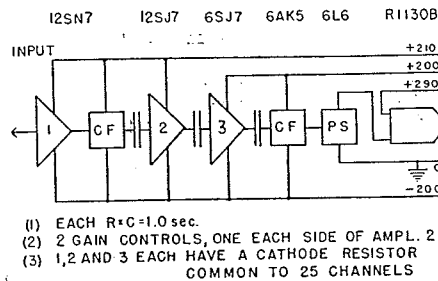


Figure 6. Block diagram of a single channel from the group of 25

The preamplifier of Figure 3 is amplifier stage 1 and the first CF (for cathode follower) in this figure. The 25 type-12SN7GT tubes are in a unit near the brain, connected by cables to the standard 6-foot by 22-inch rack containing the rest of the amplifier and power stages. The second cathode follower (CF) before the power stage (PS) furnishes a low-impedance source for the 6L6 grid current. The +200-, +210-, and -200-volt supplies are electronically regulated within about ± 50 microvolts. The +290 volts is supplied by five unregulated power supplies, containing five VR-75 tubes for constant screen-grid potential in the 6L6 tubes. The screens of the 12SJ7 tubes and the 6SJ7 tubes are at 45 volts with respect to the cathode on two separate B batteries. The heaters of the 12SN7 and the 12SJ7 tubes are on two 6-volt storage batteries, in series, cascaded to a 24-volt and a 48-volt battery to a 110-volt d-c line which supplies the required, steady-state 15 amperes of heater current. The starting warm-up transient current (between 60 and 70 amperes for the first few seconds) is supplied by the 12-volt battery. The R1130B tube is the glow tube of Figure 3; it is manufactured by the Sylvania Company. The peak current through the glow tubes is limited to 30 milliamperes by a plate and a cathode resistor in each 6L6 circuit. The over-all pass-band of these amplifiers extends from about one cycle per second to 750 cycles per second (one-half amplitude points)

The limitations of this type of action are discussed subsequently.

This type of circuit was chosen because it gives a type of differential action with a minimum number of tubes per channel (one per stage). If we had used the usual type of differential amplifier, using two tubes per stage per channel, we would have had 300 tubes to wire in, select, and maintain, instead of the 150 we now have.

GLOW TUBES

The glow lamps are Sylvania type 1B59/R1130B, a hollow-cathode (one millimeter inside diameter) end-on view glow-discharge tube. The light intensity output varies, in our circuit, in an approximately logarithmic fashion with the 6L6 grid voltage. The spectral distribu-

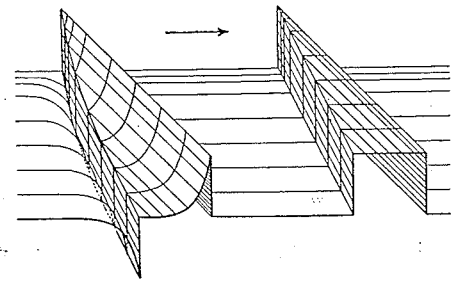


Figure 7. Isometric drawing of the "boat-hull" distortion of a rectangular traveling wedge by a 2-dimensional array of R-C coupled amplifiers

In this "snapshot" diagram, the right-hand figure is a rectangular wedge of increased potential difference (y axis) traveling in the direction of the arrow (x axis) over a 2-dimensional array (x and z axes) of electrodes. The left-hand figure is the resulting output from an array of amplifiers, each of which has a single R-C-coupled link. The "long" end of the wedge is five times R-C in "length," that is, the ratio between the length of the long end (measured in the moving co-ordinates fixed to the wedge), and its velocity relative to the x axis (fixed to the electrodes) is equal to five times the time constant of the amplifiers. The "short" end of the wedge has a value of about RC/100. A direct-coupled amplifier array would give an undistorted picture of the wedge. Considering this diagram as representing increased light intensity upwards (+y axis), and decreased light intensity downwards (-y axis), the picture (say, a single frame of a motion picture) of the wedge would be a bright triangle against a darker background. The half "boat-hull" (left-hand figure) would be a bright leading edge shading off to a dark trough followed by a brightening trailing tail. Of course, with multiple, cascaded R-C links, the picture becomes more complex. This is an example of a type of distortion to be allowed for in interpreting the results with the present apparatus. With the present 25 amplifiers, the two ends of the wedge are at about two seconds and four milliseconds

tion is a series of lines and bands throughout the visible spectrum, most intense in the yellow-red end but strong enough in the blue to use blue-sensitive film for recording. We have found that the tube life varies inversely with about the eighth power of the mean current through the tube. Therefore, we put in plate and cathode resistors in the 6L6 power stage to limit the maximum current to 30 milliamperes (about 250 hours life at this current, steady state). We operate at a mean current of 9.0 milliamperes through each R1130-B. There is some phase shift in these tubes—minimal in the blue region and maximal in the infra-red; this "hysteresis" is apparently due to heating of the cathode walls.

In order to have our sources appear larger than one millimeter in diameter at the camera, each source has a 30-millimeter-diameter lens which focuses an image of the source on the camera lens. This arrangement gives the camera a view of a 30-millimeter diameter source (at 82 centimeters) of about the apparent brilliance of the 1-millimeter cathode glow. All lenses are in a spherical surface (radius 82 centimeters) whose center is at the camera lens; thus all the 25 optic axes pass through the camera lens. The camera lens is focused on the lens bank to give bright images of the lenses on the film.

MOTION PICTURE CAMERA

As was expected, we found that 16 and 64 frames per second were recording rates which were too slow for the waves found in the brain (Figure 2). At present, we are using a Bell and Howell model 70-G Superspeed camera with electric motor and 400-foot magazines, which photographs at 128 frames per second. This is definitely a compromise: we have the amplifier pass band and the light intensity to go to higher frame rates (350 frames per second); some of the phenomena already seen require higher film rates. At 128 frames per second, 400 feet of record accumulates in 2 minutes of recording time; at 384 frames per second, 1,200 feet accumulates in two minutes; at normal projection speed (16 frames per second), the 400 feet takes 16 minutes and the 1,200 feet takes 48 minutes to see once. Thus, the time taken in viewing the records from a long experiment sets our present limit on film rate. The problem is to obtain the maximum amount of data using the minimum amount of film.

With the present equipment, the light available can be best shown by an example: Super XX film with a Corning number 2404 (red) filter at 128 frames per second is exposed at a shutter aperture of $f 11$ for the results shown in the later figures.

NUMBERING OF CHANNELS

Since the electrodes, the lamps, and the film images are in corresponding square arrays, we chose the mathematical matrix notation of numbering each element by two numbers, the first corresponding to the row number and the second to the column number. Starting with 1-1 (first element) at the upper left-hand corner of the square, we thus arrive at 5-5 (the 25th element) at the lower right-hand corner. In actual use, this array may be rotated in its own plane with respect to,

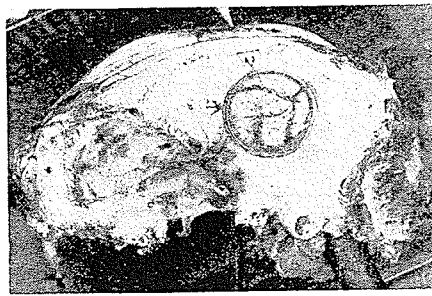


Figure 8. Location of the position of the electrode array with respect to skull and brain landmarks in a given animal (cat)

A $\frac{3}{4}$ -inch-diameter trephine hole is cut in the animal's skull at the desired location; a $\frac{3}{4}$ -inch-diameter lucite circle ($\frac{1}{8}$ inch thick, polished) with the electrode positions represented by holes drilled through it is placed in the hole in the skull. The arrow on the lucite indicator starts at electrode 5-3 (see text for numbering system) and terminates on the edge of the circle. Another arrow is scratched on the skull (opposite the first one) after the observer finds the desired orientation of the electrode representatives relative to the sulci visible through the hole in the skull. The lucite indicator is then removed, and is replaced by the electrode array held by a supporting guide ring screwed into the skull hole. The position of channel 5-3 is marked on this ring by another arrow which is lined up with that on the skull. At the end of the experiment the animal is perfused through the aorta with saline and then ten per cent formalin; the vessels in the sulci are injected with india ink; the lucite indicator is replaced in the skull hole; and the skull is photographed to record the electrode positions used. This illustration shows the position of the electrode array for the electro-iconograms of Figure 9

say, the camera field, or the brain coordinates. We maintain the convention that looking at the glow lamp array from the camera gives the same view of the numbers as looking at the electrode positions from outside the brain. Thus we can project a picture of the brain onto the lights and only by translation and rotation in the apparent plane of the lights correctly position the picture without turning it over. This convention avoids the necessity of picturing "mirror images" of the brain or of the array when mapping the one on the other. Our grounded return lead is numbered 0-0 to avoid confusion with any element, or any possible future element, in the array.

INSTRUMENTAL LIMITATIONS

The distortions of the input patterns seen at the output of the bavatron are those commonly seen in a single resistance-capacity-coupled amplifier, extended to an input and an output field. The usual amplitude, phase, frequency,

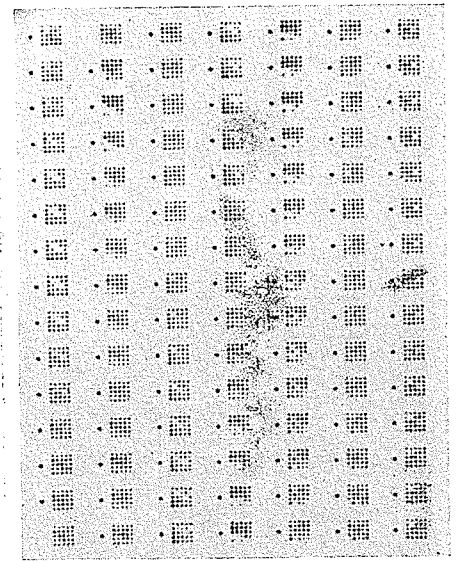


Figure 9. A sample electro-iconogram—a single response and "spontaneous" activity in the acoustic cortex of a cat

The stimulus signal light is to the left of each frame (opposite column 3, next to row 5, and hence near lamp 5-3); (The lamp array is rotated 90 degrees clockwise from the position in which numbers are assigned). A 50-microsecond rectangular pulse is fed into the earphone at the cat's contralateral ear and extinguishes the signal light for 15 milliseconds, as can be seen in frames number 14 and 15 (7.8 milliseconds for one frame-cycle); the initial "off" phase is coincident with the beginning of the click. The beginning of the response usually occurs (in other parts of this film not shown here) in 5-5 about eight milliseconds after the stimulus light goes out and spreads as a wave of lessened light intensity ("positive" wave) to include lamps 5-3, 5-4, 5-5, 4-4, 4-5, 3-5, 2-5, 1-5, as can be seen in frames 16, 17, and 18. In the motion pictures, not these "static" frames, there can be seen more complicated "gray" shadows sent out from this large "black" wave over the remainder of the array. Other waves ("spontaneous") occur in frames 3 through 10, 36 through 50, 54 through 65, and 84 through 98. By deepening the anesthesia, the response wave can be left intact but the "spontaneous" waves disappear. The electrode array position for this figure is shown in Figure 8

transient response, and differential action distortions are all seen as distortions of the input field at the output field.

The transient response (or "time-constant") distortion and its limits are shown and discussed in Figure 7; this distortion type is not discussed any further here.

The differential action distortion is due to the type of design of the amplifier system (discussed in the foregoing). Some examples show the distortions to be ex-

pected. (1) All input grids but one are fixed in potential at, say, ground level. The one grid is shifted briefly from the rest by, say, minus 1.0 millivolt. The corresponding output lamp for the change channel decreases its intensity briefly to a value corresponding to -1.0 millivolt. However, the other 24 outputs increase their intensity at the same time an amount corresponding to $+1/24$ millivolt at their input grids. Hence, at the output, the brief negative "hollow" in the input field is seen as a "negative" hollow plus a simultaneously low surrounding positive "plateau," which is created in the bavatron itself. (2) One input grid is fixed at ground potential; the other 24 are raised to $+1/24$ millivolt at the output; the same "hollow" and "plateau" is generated as in example (1). (3) The negative 1.0-millivolt input field is extended to include 12 inputs, the remaining 13 being fixed. At the output, the excited 12 channels show the extended negative hollow; the fixed 13 channels show an enhanced positive plateau equivalent to $+12/13$ times 1.0 millivolt at the 13 input grids. (4) The 13 inputs are excited in a positive direction $+12/13$ times 1.0 mv.; the 12 inputs are fixed. The same output pattern is seen as with example (3).

Thus, for each output pattern, there are at least two input patterns which could generate that output. This ambiguity of meaning of the output pattern is derived solely from the fact that the differential action of this circuit generates outputs each of which is a difference from the mean value of all outputs and that this mean value tends to remain constant. The importance of this ambiguity in actual brain pattern recordings is being investigated and evaluated at the present time.

In order to minimize channel-to-channel discontinuities with respect to amplitude, phase, and frequency distortions, the resistors and the capacitors of the first and second $R-C$ links (Figure 6) are matched to within ± 0.5 per cent. The tube gains were found to be within one per cent for all stages but the first; in the first stage, the tubes are selected and matched as described in the foregoing. Thus, these three types of distortion are at least made uniform enough over the array for practical usage.

COMPROMISES

In developing this instrument our purpose has been to develop a workable apparatus in the shortest possible time and to use it to test the hypothesis that the method is valuable and even necessary.

In the development, compromises were made to achieve that purpose. In brief, the compromises result in the following limitations of the range of performance:

1. From electrophysiological data in the literature, we know that we are not recording events of great value which lie outside our pass band.

2. Within our pass band, our time measurements (of latency and of response times) have a lower limit of one frame cycle (7.8 milliseconds) because of the intermittent nature of the recording.

3. Our measurements of the amplitude of the signals is still limited to somewhere between 10 and 50 per cent, depending on the many photographic variables involved.

Despite these limitations, we believe that our results show that the method is valuable and necessary, and that further development of the technique is desirable. We hope that our results will serve to stimulate the growth of new techniques for picking up and recording electroiconograms of greater range and hence of greater value than ours are at present.

FUTURE DEVELOPMENT

In future instruments we look for the following developments:

1. Many more channels than our 25. We think that this is the most important aspect to be developed.

2. Wider pass band for each channel, especially in the very-low-frequency region.

3. A continuous recording system, which can make full use of the available pass band, and yet from which one can reproduce the square array type of output field.

4. A compact input assembly which can be placed near the animal.

5. A minimum number of controls and a maximum stability in all required adjustments and components.

6. Construction which allows rapid replacement of the key units in each channel.

7. Designs of replaceable units which can be serviced rapidly.

The first improvement, many more channels, is desired because of the factors outlined in the beginning of this article. Watching our records is a strong stimulus to pursue this development—various patterns travel into and out of our input field to and from unobserved regions in every record we have taken to date.

The second development we consider to be necessary from data gathered by other workers, and from the rather high rate of occurrence in our records of phenomena like that presented in Figure 7.

The third improvement would improve our time measurements, and presumably could be designed to shorten considerably

the length of record required to record the same events with the same, or better, time resolution.

Input lead length is limited by the presence of various interfering fields (60-cycle-per-second line, radio-station emissions, and so forth); this fact determines the fourth requirement.

Items 5, 6, and 7 are part of sound accepted practice for any multi-channel system (telephone, telegraph, radio, and so forth).

Results

A sample of a record is presented in Figure 9. These static reproductions sacrifice the dynamic character of the phenomena as seen in the motion pictures. In viewing a motion picture of this steady pattern of lights each of whose intensity is different over the array, the visual system of the observer adapts to the steady motion picture and readily detects small changes in the pattern when they occur. This is not true of the static pictures in these figures; it is much harder to detect changes, especially if they are small and take place gradually over a large number of frames.

For best "seeing" of the patterns in the motion pictures, it has been found that the whole array of lamp images should subtend a visual angle of about 1.0 degree to about 0.1 degree. This is in the region of foveal vision in which visual acuity is at its highest, in which persistence of vision is most effective, and in which the "phi" effect is best.

The results to date are restricted to records of the activity seen on cat brains with a 2-millimeter electrode interval in a region eight by eight millimeters (which is about $1/20$ th of the total cat cortex). In general these records show that in such an area the activity does have organized forms and figures which have a size comparable to the area observed; hence adjacent zones, each containing 120,000 or so cells, do fire in an ordered fashion, either synchronously or sequentially. A brief summary of our results to date is as follows:

1. In the anesthetized animal, the cortical responses to visual and auditory stimuli in the primary afferent areas spread in a definite way away from the focus first activated by the afferent volley to the cortex.

2. The spontaneous activity of the conscious animal has traveling, shifting figures which have varying velocities and forms depending on previous stimuli and on other, as yet unknown, factors.

3. "Sleep waves" and "barbiturate

waves" have fairly simple forms which sometimes travel and sometimes appear as spreading figures starting in a small area, "growing" around that area, and fading out in place.

The details of these results are being prepared for publication elsewhere.

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